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COMPARISON OF PROCESSING PROPERTIES AND PRODUCT PROPERTIES OF BETA III TITANIUM ALLOY POWDER METAL (PM) AND INGOT METAL (IM)

UNIVERSITY OF CINCINNATI
PROCESSING AND HIGH TEMPERATURE MATERIALS BRANCH
METALS AND CERAMICS DIVISION

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AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
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Processing properties of Beta III titanium alloy powder metal (PM) and ingot material (IM) were compared. Both materials were processed under the same conditions (extruded at 760°C and 954°C with 4:1, 6:1 and 10:1 reduction ratios, extruded and forged at 760°C and 954°C and given STA and STA+OA heat treatments) No significant differences were noted between the processing properties of these materials except for the slightly higher extrusion pressures required for the powder metal (PM) at 954°C.

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Room temperature mechanical properties of the powder metal (PM) and ingot material (IM) products processed under the same conditions were compared with the following results:

1. Similar tensile properties in the STA and STA+OA conditions.
2. Similar fracture toughness values in the STA condition.
3. Slightly lower fracture toughness values for the powder metal (PM) product in the STA+OA condition.
4. Powder metal (PM) product notched fatigue properties equal or inferior to those of the ingot metal (IM) products.
5. Significantly lower smooth fatigue properties for the powder metal (PM) products.

Abnormal fracture initiation sites were found by Scanning Electron Microscope examination in the fracture surface of powder metal (PM) smooth fatigue specimens. The presence of these sites in the powder metal (PM) products are considered the cause for that material having lower properties than ingot metal (IM) products processed under the same conditions. It is believed those sites are the result of incomplete welding of adjoining powder metal particle surfaces or due to the presence of fine foreign particles in the cavities, which were not detected by Scanning Electron Microscope examination of the fractured surfaces.

FOREWORD

This report was prepared by the University of Cincinnati, Cincinnati, Ohio under USAF Contract F33615-73-C-5097. The work was initiated under Project 7351, "Metallic Materials", Task No. 735108, "Processing of Metals". The research was conducted in the Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio, by Dr. N. Birla of the University of Cincinnati, Cincinnati, Ohio and Messrs. Vincent DePierre and A. M. Adair of the Air Force Materials Laboratory.

This report covers work performed from February 1975 to February 1976. It was submitted by the authors in April 1976.

The authors gratefully acknowledge the assistance of Messrs. F. J. Gurney, T. M. Brown, T. E. Jones and M. M. Myers of the Westinghouse Electric Corporation, Astronuclear Laboratory and Mrs. A. Kiefer of Monsanto Corporation, Wright-Patterson Air Force Base, Ohio for execution of the experimental program.

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SECTION I

INTRODUCTION

United States Air Force interest in powder metallurgy stems largely from the potential benefits obtainable by use of metal powders, instead of ingot materials, for the production of metal products. These benefits include reduction in production costs and improved service performance of aerospace parts. Metal powder processing may furnish lower production costs by reduction of the number of processing operations to convert raw materials to finished parts and by minimization of scrap losses and machining. Because inherently they have finer grains and less macrosegregation than cast ingot materials, metal powders may also provide the following processing advantages over ingot material for metalworking operations:

1) Greater resistance to fracture during deformation;
2) Lower deformation loads for hot working operations;
3) Less requirement for homogenization treatment.

In addition, metal powders have the potential for furnishing products with better service properties (such as tensile properties, fracture toughness and fatigue) because of their fine grain size and homogeneity.

Titanium alloys have very attractive service properties (such as high strength, toughness and corrosion resistance) for aerospace applications. However, the high unit costs for finished titanium alloy parts limit the full utilization of these materials because of economic considerations. Major factors controlling the cost of titanium alloy parts are raw materials and processing (such as machining) costs. Methods for reduction of these costs are of vital importance to the U.S. Air Force. The use of titanium alloy powders, instead of ingot material, for the production of metal products is a very promising cost reduction method. Therefore, the Air Force Materials Laboratory has sponsored programs to quantitatively define the production cost reductions and improve service properties possible through cost reductions and improved service properties possible through titanium alloy powder utilization for manufacturing aerospace hardware.

The Air Force Materials Laboratory program, described in this report, was directed at exploring the use of titanium alloy metal powders instead of ingot material in metalworking operations for obtaining possible processing advantages and/or improved product service properties. A Beta III Titanium Alloy (Ti-11.5Mo-6Zr-4.5Sn) was selected for this investigation.

SECTION II

MATERIALS, PROCESSING AND TEST PROCEDURES

1. MATERIALS

The Beta III titanium alloy was purchased as 76mm diameter hot-rolled bars from Crucible Incorporated, Colt Industries. Some of the bars were set aside for machining into extrusion billets; the remainder were converted to powder (-35 mesh) by Nuclear Metals using the Rotating Electrode Process (REP). The chemical composition of the bar and powder is given in Table 1 and sieve analysis of powder is shown in Table 2.

Optical microscopic examination (1) showed the bar stock had a typical hot-rolled microstructure and the powder a typical cast dendritic microstructure. Scanning Electron Microscopic examination (1) showed the powder particles for the main part were spherical in shape with smooth surfaces. Occasionally elliptical particles were observed and the impingment of a smaller spherical particle on a large one could be seen.

Room temperature tensile and fracture toughness properties of the bar stock were made by the procedures later outlined in Section II 3. The properties were determined for the bar stock in the following conditions:

1) As-Received
2) As-Received plus Solution Heat-Treated (ST) at 760°C (1400°F) for 30 minutes and Water Quenched
3) As-Received, ST and Aged (STA) at 482°C (900°F) for 8 hours and Air Cooled

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(1) N.C. Birla, V. DePierre and A.M. Adair, "Consolidation of Beta III Titanium Alloy Spherical Metal Powders by Hot Swaging", Air Force Materials Laboratory Technical Report 76-22, March 1976.

4) As-Received, STA and Overaged (OA) at 593°C (1100°F) for 2 hours and Air Cooled.

The results are reported in Table 3 and indicate excellent quality Beta III titanium alloy.

Optical microscopic examinations were made of the bar stock material in the as-received plus solution treat and as-received plus solution treated and age (STA) conditions to provide photomicrographs of bar stock material microstructure for comparison with microstructures of the products produced in this investigation. The bar stock microstructures are shown in Figure 1.

Billets, 76mm in diameter and 150mm long, were machined from the bar stock. Metal powder with a poured density of about 62% was encapsulated in 1018 steel containers of the same overall dimensions which were encapsulated and sealed as described in Appendix A before extrusion.

2. PROCESSING

a. Extrusion and Forging

The machined bar stock billets and powder-filled containers were processed in the Air Force Materials Laboratory 0.31MN (700 Ton) instrumented experimental horizontal extrusion press (2). The processing conditions are listed in Table 4 and were selected to determine the processing behavior of the powder-filled containers as well as the effects of reduction ratio and extrusion temperatures on the extent of powder-particle consolidation and mechanical properties in the extruded PM product. Extrusions of the bar stock

(2) V. DePierre, "Experimental Measurement of Forces During Extrusion and Correlation with Theory" Trans. ASME Journal of Lubrication Technology, July 1970, Pages 398-405.

billets were made under identical conditions as the powder-filled containers to provide extrusion data for comparison of ingot metal (IM) and powder metal (PM) processing behavior and to obtain extruded IM product for comparison of extruded IM product properties with extruded PM product properties.

During extrusion, deformation loads and ram speeds were recorded for each extrusion (2). Dimensional measurements and visual examinations were made on the extruded products. Reduction ratios for each extrusion were calculated by dividing the upset billet cross-sectional area in the extrusion liner by the product cross-sectional area. Blanks for longitudinal tensile, fatigue and fracture toughness tests were cut from the 6:1 and 10:1 extrusions. The 4:1 extrusions were cut into 70mm length pieces for forging into a flat shape to provide specimens for both longitudinal and transverse tensile and fracture toughness tests.

The forging blanks were coated with a lubricant (Polygraph), heated to forging temperature (same as the extrusions temperature) in an air electric resistance heated furnace, held at temperature for 60 minutes and then transferred to a die (Figure 2) specially designed to minimize flow in the length (70mm) direction. The special die was located on the bottom platen of the AFML 500 Ton Forging Press and was maintained at 600°F with Fiske 604D as a die lubricant.

The ram of the forge press was moved at a speed of 38-50 mm/sec (1½-2 in/sec) to reduce the blank height 50% and to obtain the final test blank shown in Figure 3.

b. Heat Treatment

Before machining of test specimens, all blanks were given the maximum strengthening heat treatment (STA) for Beta III titanium alloy (i.e.

760°C (1400°F) for 30 minutes, water quench plus 482°C (900°F) for 8 hours and air cool). Some of the test specimens machined from the STA heat-treated blanks were overaged (OA) at 593°C (1100°F) for 2 hours followed by air cooling. For the STA treatment, specimens were placed in protective stainless-steel bags containing titanium sponge and heat-treated in air in an electric-resistance heated furnace. For the OA treatment, machined STA heat-treated specimens were inserted into a quartz tube evacuated to 10^{-5} torr or better, placed in an air electric-resistance heated furnace, pulled out of the furnace and air cooled.

3. TEST PROCEDURES

a. Tensile Tests

Standard R-3 and R-5 tensile specimens (ASTM Designation E8-69) were machined from extruded and forged heat-treated blanks respectively. All specimens from the extruded material were in the longitudinal direction; specimens from the forged blanks were selected as illustrated in Figure 3. Room temperature tensile tests were performed on a 44.5KN (10,000 lb) Instron machine with a cross-head speed of 0.02mm/sec (0.05 mm/min).

b. Fracture Toughness

Standard charpy V-notch specimens were tested in slow bending with three point loading to determine fracture toughness (K_Q) values. These specimens were precracked by fatigue loading prior to testing. Specimens for 10:1 extrusion ratio were tested for all the processing conditions and both in STA and STA+OA heat treatment condition, while for 6:1 extrusions only a few specimens were available for testing.

c. Fatigue Tests

For each processing condition extrusions (10:1 ratio only), both notched and unnotched specimens in STA condition were machined and tested at room temperature. Schenk axial loading fatigue machines were used, a 12,000 lb capacity machine for unnotched specimens and a 4000 lb capacity one for notched specimens. The specimens were tested under tension-tension loading at R=+0.1. The specimens were 3 inch long, 0.200 inch in dia. in the center of a 2" rad. unnotched specimen, and 0.28" in dia. with a 0.0075" root rad. center notch for the notched specimens. Unnotched specimens had a K_t=1.0 and notched specimens a K_t=3.0.

d. Metallography

Microscopic examination of the consolidated product and in heat-treated condition was carried out by standard techniques using Krolls etch. In some cases it was found necessary to use a cleaning etch (1ml HF + 2 ml HNO_3 + 50 ml H_2O + 50 ml H_2O_2). The same examination was used to determine the product integrity. Scanning Electron Microscopy (SEM) was performed on fractured surfaces to determine the mode of failure and origin of failure due to the presence of foreign particles, if any, or any other abnormality.

e. Chemical Analysis

The chemical analysis as a check on interstitials was done on some of the specimens to see if there is any interstitial pick-up during processing or heat treatment.

SECTION III

RESULTS AND DISCUSSIONS

1. PROCESSING RESULTS

a. Deformation Pressures

Extrusion results for bar stock (IM) and powder (PM) Beta III titanium alloy are reported in Table 5. A plot (Figure 4) of the minimum extrusion pressure versus the natural logarithm of the reduction ratio provides a measure of the bar stock and powder metal material flow stress under the actual processi conditions (2). Figure 4 indicates no significant differences between the deformation pressures required to extrude the two materials. However, since the powder metal material was encapsulated in mild steel, the deformation pressures for the powder metal reflect the combination of forces required to extrude 1018 steel as well as the powder metal. AT 760°C (1400°F) the pressures for extrusion of 1018 Steel are approximately equal to those for Beta III titanium alloy; at 954°C (1750°F) the pressures for extrusion of 1018 Steel are lower than those required for Beta III titanium alloy. Therefore, the pressure results indicate that the flow stress values under processing conditions are equal for bar stock (IM) and powder metal (PM) Beta III titanium alloy at 760°C (1400°F) and not equal at 954°C (1750°F) with the powder metal having a greater flow stress than the ingot metal.

b. Product Integrity

The bar stock (IM) and powder metal (PM) extrusions produced under the conditions covered by this investigation, were found to be sound by visual examination and, with one exception, contained neither macroscopic nor microscopic voids. The exception was the 4:1 extrusion (5652) produced by Processing Condition 7 (954°C precompaction followed by 760°C extrusion). This extrusion showed prior particle boundaries as well as voids under microscopic examination. Although 4:1 extrusions from Processing Conditions 3 and 5 (760°C extrusion temperature) were completely sound, the existence of voids and prior particle boundaries in the microstructure of the 4:1 extrusion product from Processing Condition 7 indicate that 4:1 extrusion of Beta III titanium alloy powder at 760°C (1400°F) does not insure complete densification and welding of adjoining particle surfaces. All other processing conditions investigated furnished complete consolidation of the powder.

2. MECHANICAL TEST RESULTS

a. Tensile Properties and Fracture Toughness Values

The room temperature tensile properties and fracture toughness values are listed in Table 6 for the bar stock (IM) products and in Tables 7 and 8 for the powder metal (PM) products. A comparison of the results for both bar stock and powder metal processed under the same conditions shows:

1) No significant differences in tensile properties in the STA and STA+OA conditions;
2) No significant differences in fracture toughness values in the STA condition;
3) In the STA+OA condition, the bar stock products have slightly higher fracture toughness values than the powder metal products.

b. Fatigue Results

(1) Unnotched Fatigue Behavior

The data obtained on STA smooth fatigue specimens for all the processing conditions is shown in Table 9. The comparison of data for both wrought and powder product is shown in Figure 5. While the two materials show nearly identical fatigue behavior at the higher stress levels, there is a definite trend of superiority foı the wrought product as the endurance limit stress is approached. There are no significant differences in smooth fatigue behavior among the compaction and processing variables for the powder material.

(2) Notched Fatigue Behavior

Data obtained on STA notched fatigue specimens for all the processing conditions is shown in Table 10. The comparison of data for both wrought and powder product is shown in Figure 6. The two materials show essentially the same fatigue behavior under notched conditions. The endurance limit for both is about 50 KSI.

3. MICROSTRUCTURES

Representative microstructures of the processed materials in the as-extruded condition are shown in Figures 7, 8, and 9. Figures 7 and 8 are micrographs of the products produced with an extrusion ratio of 4:1 at 760°C and 954°C respectively. Figure 9 has micrographs of the products produced with an extrusion ratio of 10:1 at 760°C and 954°C and is also representative of the products produced with an extrusion ratio of 6:1. The 760°C extruded products show very few recrystallized grains except the one with Processing Condition 5, Figure 9c. Otherwise the bar stock extrusions (Processing Condition 1) do not show any appreciable microstructural difference from those powder metal extrusions extruded at 760°C. All the 954°C extruded products show recrystallized grains with the powder product grain sizes slightly larger than those of the bar stock product. The recrystallized grains of both the bar stock and powder metal extrusions were significantly smaller than the grain size of the original bar stock (Figure 1a). This indicates the occurrence of recrystallization in both bar stock and powder metal materials during 954°C extrusion.

As noted under "Project Integrity Section III 1b", only one of the extrusions, showed any prior particle boundaries or voids. The exception is shown in Figure 7d. As shown in Figure 10b, subsequent 50% forging reduction at 760°C of 4:1 extruded samples did not close the microvoids. As illustrated in Figures 11, 12, 13 and 14, none of the other forged pieces contained microvoids. However, considerable grain growth is evident in the blanks (Figures 12, 13 and 14) heated to 954°C for forging. No grain growth is noted in the blanks (Figures 10 and 11) heated to 760° for forging. Basically there is no differences in the microstructures of bar stock and powder metal forgings processed in the same manner.

The microstructures of the extruded products in the STA and STA+OA heat-treated conditions were examined to determine if there were any microstructure differences between bar stock and powder metal products. Representative microstructures are shown in Figure 15 and 16. Again no differences were noted for the two materials processed in the same manner.

Several fractured surfaces of tensile specimens were examined under the Scanning Electron Microscope and did not show any abnormal condition to which origin of failure or premature failure could be attributed. Presence of any foreign particle was not observed.

Fracture surfaces near the origin of failure of unnotched fatigue specimens were also examined under the Scanning Electron Microscope. Representative Scanning Electron Microstructures are shown in Figures 17 and 18. None of the fracture surfaces showed any presence of foreign particles. Figures 17 (A) and 17 (B) for bar stock product show a smooth intergranular fracture surface; Figures 17 (C), 17 (D) and 20 for powder metal product show abnormal initiation sites giving rise to premature failure. It is believed those sites are the result of incomplete welding of adjoining powder metal particle surfaces or due to the presence of fine foreign particles in the cavities, which were not detected by SEM examination of the fracture surfaces.

4. CHEMICAL ANALYSIS RESULTS

Check chemical analysis for interstitial contents of bar stock (IM) and powder metal (PM) products are furnished in Table 11. Comparison of original materials (Table 1) and processed materials (Table 11) analyses shows no significant changes in interstitial contents.

SECTION IV

CONCLUSIONS

1. Powder metal (PM) of Beta III titanium alloy has processing properties similar to bar stock (IM) Beta III titanium alloy in metalworking operations at 760°C (1400°F) but requires slightly higher deformation pressures than the bar stock (IM) at 954°C (1750°F).

2. Room temperature mechanical properties of powder metal (PM) products are inferior to the properties of bar stock (IM) products produced under the same processing conditions. The powder metal (PM) product has slightly lower fracture toughness values in the STA+OA condition, notched fatigue strengths equal or inferior and smooth fatigue properties significantly lower than the bar stock (IM) products.

3. The presence of abnormal fracture initiation sites in the powder metal (PM) products are the cause for that material having lower mechanical properties than bar stock (IM) products.

APPENDIX A

ENCAPSULATION OF METAL POWDERS IN CONTAINERS

Containers to encapsulate the powder for subsequent extrusion were fabricated from commercial 1018 steel tubes and bar stock with the following dimensions:

Part A, Primary Tube (153mm long, 73mm O.D. and 61mm I.D.) cut from tube stock.

Part B, Bottom Closure (61mm O.D. and 25mm thick) cut from bar stock.

Part C, Top Closure (61mm O.D., 13mm I.D. and 25mm thick) cut and machined from bar stock.

Part D, Leading Tube (200mm long, 13mm O.D. and 10mm I.D.) cut from tube stock.

All parts were welded together to form a container with a closed bottom and an open leading tube in the container top. The welded containers were tested for leaks by filling them with air at $1.1 N/mm^2$ (160 psi) and rotating the air-filled assembly under water to detect any adhering or escaping air bubbles. Leaky assemblies were made pressure-tight by weld repair. Only pressure-tight assemblies were utilized for powder encapsulation.

Powders were poured through the leading tube (Part D) into the primary tube (Part A). After filling, a vacuum pump was attached to the free end of the leading tube (Part D) and the container was then evacuated at room temperature to a pressure of $1 \times 10^{-2} N/mm^2$ (10^{-4} mm Hg) or better. With the vacuum system operating continuously, the container was placed in a furnace preheated to $644^{\circ}K$ ($700^{\circ}F$) and held for 2 hours to drive off absorbed volatile components.

The container was then allowed to cool to room temperature and sealed by crimp-welding of the leading tube (Part D) while the evacuation pump was still operating. The sealed container now served as a portable vacuum chamber and was ready for metalworking processes.

APPENDIX B

PRECOMPACTION OF METAL POWDERS IN CONTAINERS BEFORE EXTRUSION

Compaction of metal powders, encapsulated in containers by the procedure described in Appendix A, was performed before extrusion to obtain fully dense metal powder billets. For precompaction the powder-filled metal container was heated to the required temperature and then inserted into the open end of the liner of an extrusion press which had "blank" tooling at the exit end of the liner and a split mild steel sleeve in the liner adjacent to the blank tooling. After the powder-filled container was inserted into the liner, full press capacity 1.24KN/mm^2 (180 KSI) was immediately applied for 60 seconds. Then the load was released from the billet, the blank tooling removed and the compacted container now enclosed in the mild steel sleeve was pushed out of the liner by the press ram. The split sleeve was removed from the compacted billet and the billet allowed to cool in air. Removal of the split sleeve left the compacted billet with outside diameter of the correct size for insertion in the extrusion liner for extrusion without any additional machining. The compacted metal powder billet was extruded by normal extrusion operations into bars.

TABLE 1

THE CHEMICAL COMPOSITION OF AS-RECEIVED BAR STOCK AND POWDER

(-35 MESH) OF BETA III TITANIUM ALLOY

ELEMENTS	WT% FOR BAR STOCK[1]	POWDER[2]
Mo	11.2	11.4
Zr	6.2	6.3
Sn	4.6	4.4
Fe	0.015	-
C	0.015	0.012
O	0.139	0.188
N	0.016	0.013
H	0.0069	0.0088

(1) Analysis supplied by Crucible Steel Company

(2) Analysed in the Air Force Materials Laboratory

TABLE 2

PARTICLE SIZE DISTRIBUTION OF BETA III TITANIUM

ALLOY POWDER (-35 MESH)

SCREEN SIZE MESH	WT% RETAINED
+40	3.9
-40+60	28.0
-60+100	52.3
-100+140	10.7
-140+200	3.5
-200+325	1.5
-325	0.09

TABLE 3

ROOM TEMPERATURE TENSILE AND FRACTURE TOUGHNESS

PROPERTIES OF AS-RECEIVED BETA III

TITANIUM ALLOY BAR STOCK

Condition	Tensile Properties				Fracture Toughness
	Yield Strength 0.2% Offset	Tensile Strength	Elongation	Reduction in Area	K_Q
	KSI	KSI	%	%	KSI $\sqrt{IN}$
As-Received	145.0	148.1	17.6	62.6	52.4
As-Received(1) +Solution Treatment	104.3	119.5	31.7	69.4	64.9
As-Received(2) +STA	176.8	180.6	7.8	16.7	45.5
As-Received plus STA+ OA	-	-	-	-	73.8

(1) Solution Treatment - 760°C (1400°F) for 30 minutes and water quenched.

(2) STA - Solution Treatment plus Aging at 482°C (900°F) for 8 hours and air cooled.

(3) STA+OA - STA plus Overaging at 593°C (1100°F) for 2 hours and air cooled.

TABLE 4

EXTRUSION PROCESSING PARAMETERS(1) FOR BAR

STOCK (IM) AND POWDER (PM)

BETA III TITANIUM ALLOY

Material	Processing Condition Number	Extrusion Parameters		Billet Pre-Extrusion Processing
		Temperature °C (°F)	Normal Reduction Ratios	
Bar Stock (IM) (2)	1	760 (1400)	4,6&10	None
	2	954 (1750)	4,6&10	None
Powder Metal (PM) (3)	3 (4)	760 (1400)	4,6&10	None
	4 (4)	954 (1750)	4,6&10	None
	5	760 (1400)	4,6&10	Pre-compacted (5) at 760°C (1400°F)
	6	954 (1750)	4,6&10	Pre-compacted at 760°C (1400°F) (5)
	7	760 (1400)	4,6&10	Pre-compacted at 954°C (1750°F) (5)
	8	954 (1750)	4,6&10	Pre-compacted at 954°C (1750°F) (5)

Notes: 1. Common Parameters - Zirconia coated H-12 steel (RC-40 to 44) steel dies with 90° included angle and square opening; billets heated at temperature in an electric resistance furnace for 2 hours; ram speed ~ 2 in/sec; container liner I.D. of 3.072 inches; die and container temperature 260°C (500°F); die and container lubrication Fiske 604D; extrusions water quenched immediately after extrusion.

2. Billet Lubrication - Corning Glass 8871 for Condition 1;
Corning Glass 0010 for Condition 2.

3. Can Lubrication - Polygraph (Graphite).

4. Nose Block of 1018 Steel heated to 788°C(1450°F) lubricated with Polygraph inserted into extrusion liner immediately before the powder-filled can.

5. Pre-compaction as described in Appendix B.

TABLE 5

EXTRUSION RESULTS FOR BAR STOCK (IM) AND POWDER (PM)

BETA III TITANIUM ALLOY

Extrusion Number	Processing Condition	Reduction Ratio	Ram Speed in/sec.	Extrusion Pressures (KSI) Maximum	/ Mimimum
		Bar Stock (IM)			
5642	2	3.97	2.1	70	54
5651	1	3.97	2.0	111	76
5643	2	6.09	2.1	90	65
5654	1	5.96	1.9	128	95
5657	1	9.5	1.7	113	111
5744	1	9.68	1.9	108	108
5745	1	9.64	1.9	111	111
5644	2	9.86	2.0	100	81
5754	2	9.65	2.1	111	84
5755	2	9.65	2.1	109	84
		Powder Metal (PM)			
5732	3	4.25	2.1	81	81
5625	4	4.15	3.4	81	54
5653	5	3.9	2.3	86	74
5646	6	4.14	2.1	61	49
5652	7	3.91	2.0	100	76
5645	8	4.16	2.1	65	54

TABLE 5 (Cont'd)

Extrusion Number	Processing Condition	Reduction Ratio	Ram Speed in/sec.	Extrusion Pressures (KSI) Maximum	/ Minimum
		Powder Metal (PM)			
5733	3	6.44	2.0	100	97
5626	4	6.56	3.0	80	65
5656	5	5.91	1.9	107	89
5648	6	6.29	2.0	80	65
5655	7	5.91	1.9	97	86
5647	8	6.41	2.0	85	70
5734	3	9.71	1.7	130	124
5735	3	9.69	1.7	130	124
5660	3	10.1	1.7	124	119
5724	4	10.1	2.0	95	89
5725	4	9.77	2.0	97	93
5627	4	10.8	3.0	95	86
5659	5	9.8	1.7	122	108
5742	5	9.7	1.9	116	111
5743	5	9.7	1.9	.	108
5650	6	9.3	2.0	97	80
5752	6	9.8	2.1	95	81
5753	6	9.8	2.0	95	84
5658	7	9.84	1.8	119	108
5740	7	9.7	1.8	119	113
5741	7	9.7	1.7	124	116
5649	8	9.8	2.0	100	86
5750	8	9.4	2.2	92	81
5751	8	9./8	2.1	92	84

TABLE 6

ROOM TEMPERATURE TENSILE PROPERTIES AND FRACTURE

TOUGHNESS VALUES OF BAR STOCK (IM) PRODUCTS

OF BETA III TITANIUM ALLOY

A. STA CONDITION LONGITUDINAL DIRECTION

Extrusion Condition (Reduction Ratio)	Forging Temperature (Percent Reduction)	Tensile Properties				Fracture Toughness
		Yield Strength (2% Offset)	Tensile Strength	Elongation	Reduction in Area	K_Q
		KSI	KSI	%	%	KSI $\sqrt{IN}$
1 (4:1)	760°C (50)	203.6	217.3	5.9	13.8	(1)
1 (6:1)	None	181.9	201.6	10.1	21.7	28.1
1 (10:1)	None	178.0	194.5	11.7	30.6	23.8
2 (4:1)	954°C (50)	198.0	205.9	3.3	2.6	33.2
2 (6:1)	None	179.0	195.1	9.3	20.6	24.5
2 (10:1)	None	173.1	188.4	9.8	22.4	23.4
	B. STA CONDITION TRANSVERSE DIRECTION					
1 (4:1)	760°C (50)	190.9	194.7	7.0	20.0	24.5
2 (4:1)	954°C (50)	192.0	205.0	8.4	13.4	32.1
	C. STA+OA CONDITION LONGITUDINAL DIRECTION					
1 (4:1)	760°C (50)	167.0	172.6	11.2	25.5	69.7
1 (6:1)	None	158.6	168.7	16.5	44.1	75.9
1 (10:1)	None	161.4	167.8	15.6	51.4	66.1
2 (4:1)	954°C (50)	160.8	165.7	9.9	21.8	62.9
2 (6:1)	None	151.9	159.5	17.6	42.8	79.9
2 (10:1)	None	-	-	-	-	72.1
	D. STA+OA CONDITION TRANSVERSE DIRECTION					
1 (4:1)	760°C (50)	151.6	157.6	11.7	45.1	62.8
2 (4:1)	954°C (50)	165.2	170.2	12.0	44.1	75.9

TABLE 7

ROOM TEMPERATURE TENSILE PROPERTIES AND FRACTURE TOUGHNESS VALUES OF POWDER METAL (PM) PRODUCTS OF BETA III TITANIUM ALLOY IN THE STA HEAT-TREATED CONDITION

A. LONGITUDINAL

Extrusion Condition (Reduction Ratio)	Forging Temperature (Percent Reduction)	Tensile Properties				Fracture Toughness
		Yield Strength (2% Offset)	Tensile Strength	Elongation	Reduction in Area	K_Q
		KSI	KSI	%	%	KSI$\sqrt{IN}$
3 (4:)	760°C (50)	201.6	204.6	4.1	9.9	29.9
3 (6:1)	None	179.4	195.5	10.7	24.2	(1)
3 (10:1)	None	179.0	201.0	10.3	25.1	(1)
4 (4:1)	954°C (50)	199.1	205.1	3.7	3.4	32.1
4 (6:1)	None	179.4	187.1	10.9	26.0	(1)
4 (10:1)	None	174.5	190.5	10.6	24.8	20.8
5 (4:1)	760°C (50)	203.0	216.0	7.1	14.2	31.4
5 (6:1)	None	182.8	200.7	10.9	23.4	(1)
5 (10:1)	None	181.0	200.5	10.7	30.3	23.8
6 (4:1)	954°C (50)	202.0	207.2	3.5	7.0	36.1
6 (6:1)	None	172.4	186.0	10.6	22.9	(1)
6 (10:1)	None	167.5	185.5	9.4	19.6	24.7
7 (4:1)	760°C (50)	207.6	219.0	7.1	13.1	25.4
7 (6:1)	None	186.8	204.3	10.2	16.6	26.0
7 (10:1)	None	181.5	198.0	10.9	28.2	(1)
8 (4:1)	954°C (50)	199.4	208.0	4.7	4.2	40.1
8 (6:1)	None	174.6	190.0	9.5	19.8	24.0
8 (10:1)	None	172.0	186.0	7.9	12.0	21.5
		B. TRANSVERSE				
3 (4:1)	760°C (50)	201.0	211.6	6.5	7.0	25.5
4 (4:1)	954°C (50)	198.6	210.2	7.6	10.4	(1)

TABLE 7 (Cont'd)

B. TRANSVERSE

Extrusion Condition (Reduction Ratio)	Forging Temperature (Percent Reduction)	Tensile Properties				Fracture Toughness K_Q
		Yield Strength (2% Offset)	Tensile Strength	Elongation	Reduction in Area	
		KSI	KSI	%	%	$KSI\sqrt{IN}$
5 (4:1)	760°C (50)	197.6	210.7	7.5	17.3	28.0
6 (4:1)	954°C (50)	194.9	205.9	7.1	16.2	24.2
7 (4:1)	760°C (50)	193.5	197.2	5.1	11.5	(1)
8 (4:1)	954°C (50)	196.3	208.7	7.4	16.3	30.1

(1) Specimen broke during pre-cracking.

TABLE 8

ROOM TEMPERATURE TENSILE PROPERTIES AND FRACTURE TOUGHNESS VALUE OF POWDER METAL (PM) PRODUCTS OF BETA III TITANIUM ALLOY IN THE STA+OA HEAT-TREATED CONDITION

A. LONGITUDINAL

Extrusion Condition (Reduction Ratio)	Forging Temperature°C (Percent Reduction)	Tensile Properties				Fracture Toughness
		Yield Strength (0.2% Offset)	Tensile Strength	Elongation	Reduction in Area	K_Q
		KSI	KSI	%	%	KSI$\sqrt{IN}$
3 (4:1)	760°C (50)	166.1	172.1	13.2	43.1	50.5
3 (6:1)	None	154.7	160.1	18.3	48.1	-
3 (10:1)	None	161.6	167.7	15.1	45.1	60.9
4 (4:1)	954°C (50)	163.6	173.4	10.6	31.2	-
4 (6:1)	None	144.3	153.4	18.8	48.6	-
4 (10:1)	None	155.2	159.6	15.1	43.8	63.8
5 (4:1)	760°C (50)	169.6	173.5	11.0	25.4	41.6
5 (6:1)	None	154.2	160.1	19.1	49.9	-
5 (10:1)	None	160.0	166.8	15.7	44.1	49.0
6 (4:1)	954°C (50)	165.5	169.5	11.6	33.7	54.0
6 (6:1)	None	143.6	149.1	17.6	47.0	-
6 (10:1)	None	153.3	158.7	17.1	44.1	55.2
7 (4:1)	760°C (50)	172.1	178.0	10.9	24.5	-
7 (6:1)	None	154.4	161.5	17.5	45.1	-
7 (10:1)	None	161.3	168.2	15.2	45.3	57.4
8 (4:1)	954°C (50)	162.3	167.7	10.1	22.9	58.8
8 (6:1)	None	146.6	152.7	16.4	38.8	-
8 (10:1)	None	150.5	154.8	15.5	30.0	69.6
		B. TRANSVERSE				
3 (4:1)	760°C (50)	168.6	173.5	11.6	31.2	41.2

TABLE 8 (Cont'd)

B. TRANSVERSE

Extrusion Condition (Reduction Ratio)	Forging Temperature°C (Percent Reduction)	Tensile Properties				Fracture Toughness K_Q
		Yield Strength (0.2% Offset)	Tensile Strength	Elongation	Reduction in Area	
		KSI	KSI	%	%	KSI$\sqrt{IN}$
4 (4:1)	954°C (50)	165.0	170.6	12.8	34.7	-
5 (4:1)	760°C (50)	164.1	170.0	14.0	34.5	36.9
6 (4:1)	954°C (50)	163.8	167.8	12.9	34.5	51.8
7 (4:1)	760°C (50)	150.8	157.2	13.0	50.1	-
8 (4:1)	954°C (50)	163.6	168.6	11.2	34.7	57.7

TABLE 9

ROOM TEMPERATURE FATIGUE DATA ON SMOOTH SPECIMENS OF EXTRUDED BETA III TITANIUM ALLOY POWDER AND BAR

STOCK IN STA CONDITION

R=0.1

Processing Condition(1)		No. of Cycles to Failure at								
Material	Processing Condition(1)	180 KSI	160 KSI	140 KSI	130 KSI	120 KSI	100 KSI	80 KSI	60 KSI	50 KSI
Bar Stock	1	$6.1x10^3$	$1.7x10^4$	$5.9x10^5$	$3.7x10^6$ $0.9x10^6$	$4.1x10^5$	$8.4x10^6$	$12.6x10^6$ N. F.		
Bar Stock	2	$2.4x10^3$	$4.1x10^3$	$6.3x10^4$	$10.7x10^6$	$14.7x10^6$ N. F.				
Powder Metal	3	$5.4x10^3$	$1.22x10^4$	$1.05x10^4$	$2.8x10^4$	$4.4x10^4$	$7.2x10^4$	$1.8x10^6$ $1.3x10^5$	$10x10^6$ N. F.	$1.7x10^7$ N. F.
Powder Metal	4	$2.7x10^3$	$1.2x10^4$	$1.05x10^4$	$2.8x10^4$	$7.2x10^4$	$2.3x10^5$	$7.6x10^6$		
Powder Metal	5	$2.3x10^3$	$7.8x10^3$	$1.9x10^4$	$3.0x10^4$	$3.0x10^4$	$9.1x10^5$	$3.5x10^6$		
Powder Metal	6	$1.8x10^3$	$1.2x10^4$	$1.5x10^4$	$2.0x10^4$	$4.5x10^4$	$8.6x10^4$	$2.6x10^6$		
Powder Metal	7	$3.3x10^3$	$1.2x10^4$	$1.3x10^4$	$8.1x10^4$	$1.1x10^5$	$4.0x10^5$			
Powder Metal	8	$3.3x10^3$	$7.4x10^3$	$1.9x10^4$	$1.9x10^4$	$3.1x10^4$	$3.4x10^5$	$1.1x10^7$ N.F.		

* Failure in threads of the specimen
N. F. = No Failure
(1) 10:1 Extrusion Reduction Ratio

TABLE 10

ROOM TEMPERATURE FATIGUE DATA ON NOTCHED SPECIMENS OF EXTRUDED BETA III

TITANIUM ALLOY POWDER AND BAR STOCK IN STA CONDITION

R-0.1
K_t=3.0

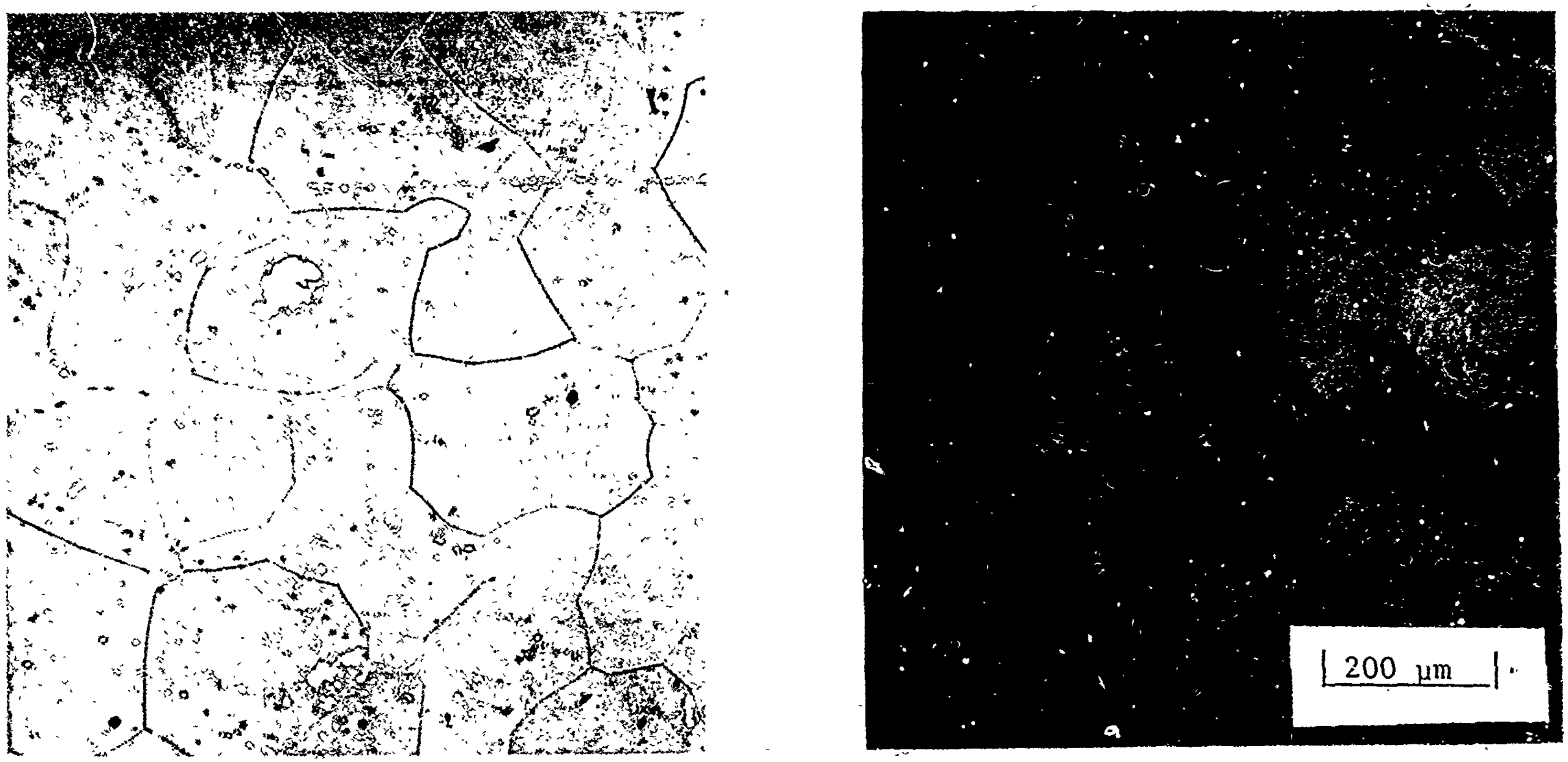
Material	Processing Condition(1)	No. of cycles to failure at				
		70 KSI	60 KSI	55 KSI	50 KSI	40 KSI
Bar Stock	1	2.1×10^{4}	4.0×10^{4}	1.0×10^{6} N. F.	1.2×10^{7} N. F.	
Bar Stock	2	3.7×10^{4}	1.2×10^{5}	1.6×10^{6} N. F.	1.7×10^{7} N. F.	
Powder Metal	3	4.3×10^{4}	3.7×10^{5}	1.3×10^{6} N. F.	1.4×10^{6} N. F.	
Powder Metal	4	1.0×10^{4}	3.4×10^{4}	5.6×10^{4}	1.6×10^{7} N. F.	
Powder Metal	5	2.3×10^{4}	1.5×10^{5}	2.1×10^{7} N. F.	1.1×10^{7} N. F.	
Powder Metal	6	1.1×10^{4}	2.9×10^{4}	-	7.0×10^{4}	1.3×10 N. F.
Powder Metal	7	2.2×10^{4}	4.4×10^{4}	6.4×10^{5}	1.6×10^{7} N. F.	
Powder Metal	8	2.8×10^{4}	1.1×10^{5}	-	2.1×10^{6}	3.2×10^{7} N. F.

(1) 10:1 Extrusion Reduction Ratio
N. F. = No Failure

TABLE 11

CHEMICAL ANALYSIS OF TENSILE SPECIMENS IN STA AND STA+OA CONDITION

Processing Condition		Carbon	Hydrogen	Oxygen	Nitrogen
No.	Heat Treatment	Wt%	Wt%	Wt%	Wt%
1	STA	-	0.0078	0.169	0.009
2	STA	-	0.0087	0.146	0.006
3	STA	-	0.0107	0.217	0.014
3	STA+OA	0.015	0.0128	0.174	0.014
5	STA	-	0.0092	0.164	0.017
6	STA	-	0.0115	0.186	0.015
6	STA+OA	0.012	0.0100	0.165	0.013
7	STA	-	0.0092	0.181	0.017
8	STA	-	0.0100	0.184	0.015
8	STA+OA	0.014	0.0087	0.174	0.012



a b

Figure 1. Micrograph of Longitudinal Section of As-Received Beta III After Heat Treatment.
(A) Solution Treatment, (B) STA.

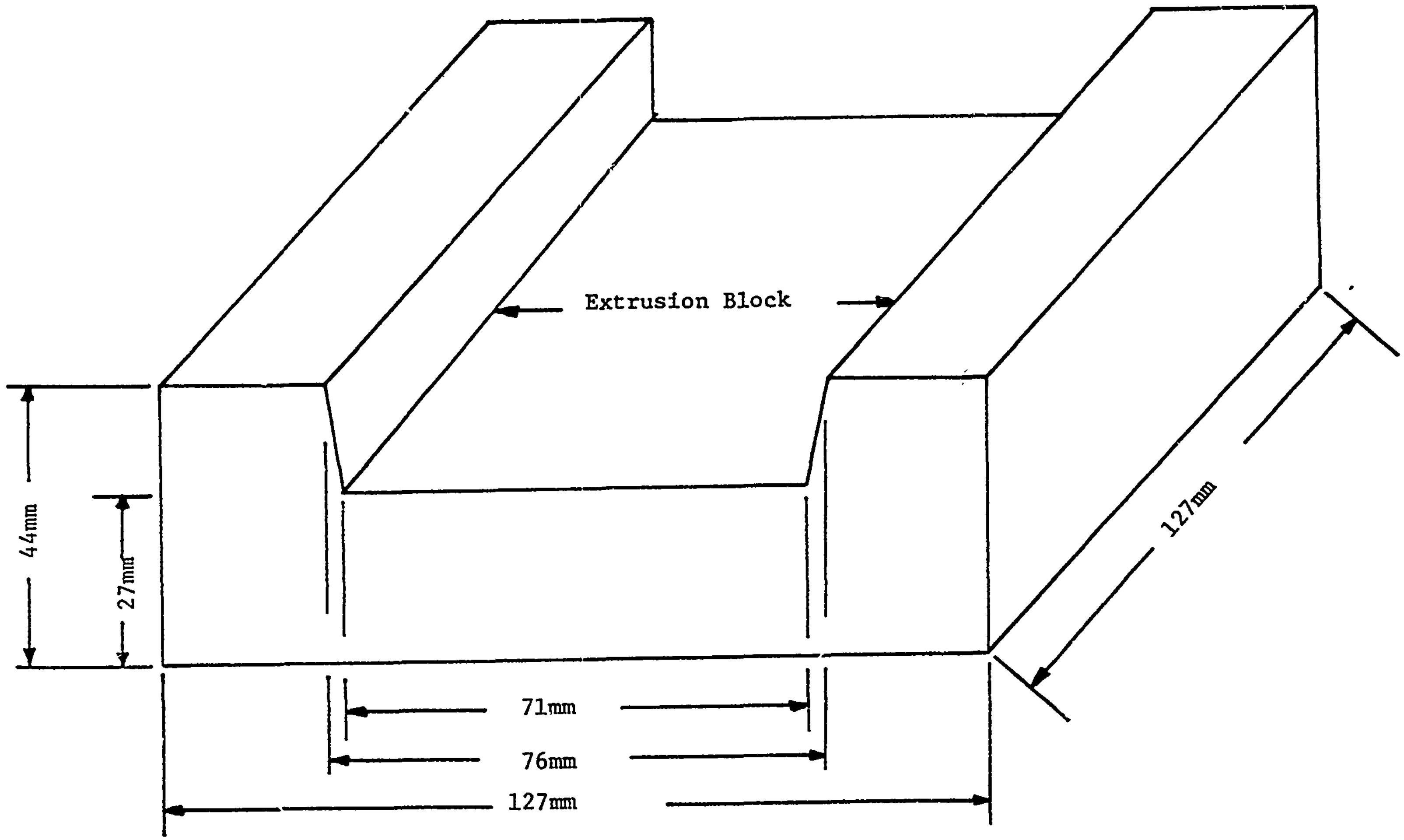
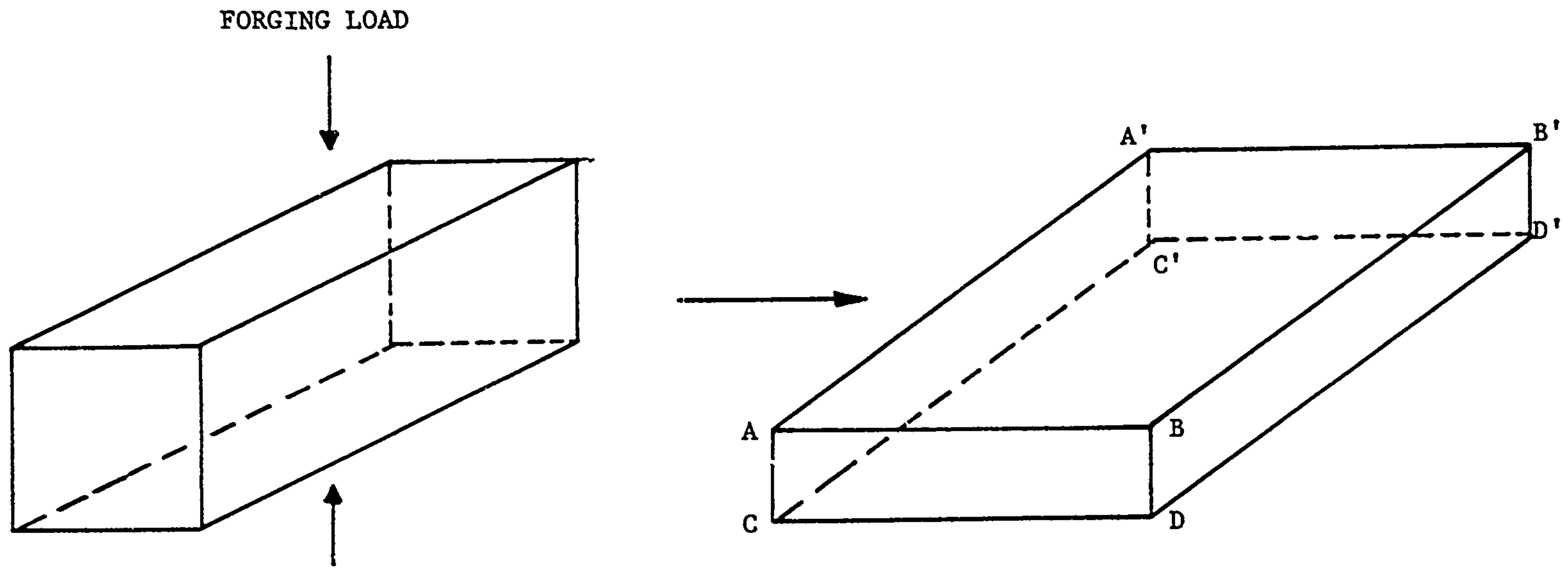


Figure 2. Schematic Diagram of Die Designed for Forging Operation.



L - Tensile specimen has its long axis along AA' direction.

T - Tensile specimen has its long axis along AB direction.

L_1 - Fracture toughness specimen has notch on AA'BB' surface.

T_1 - Fracture toughness specimen has notch on ABCD surface.

Figure 3. Schematic of Forging Work Piece Before and After the Forging.

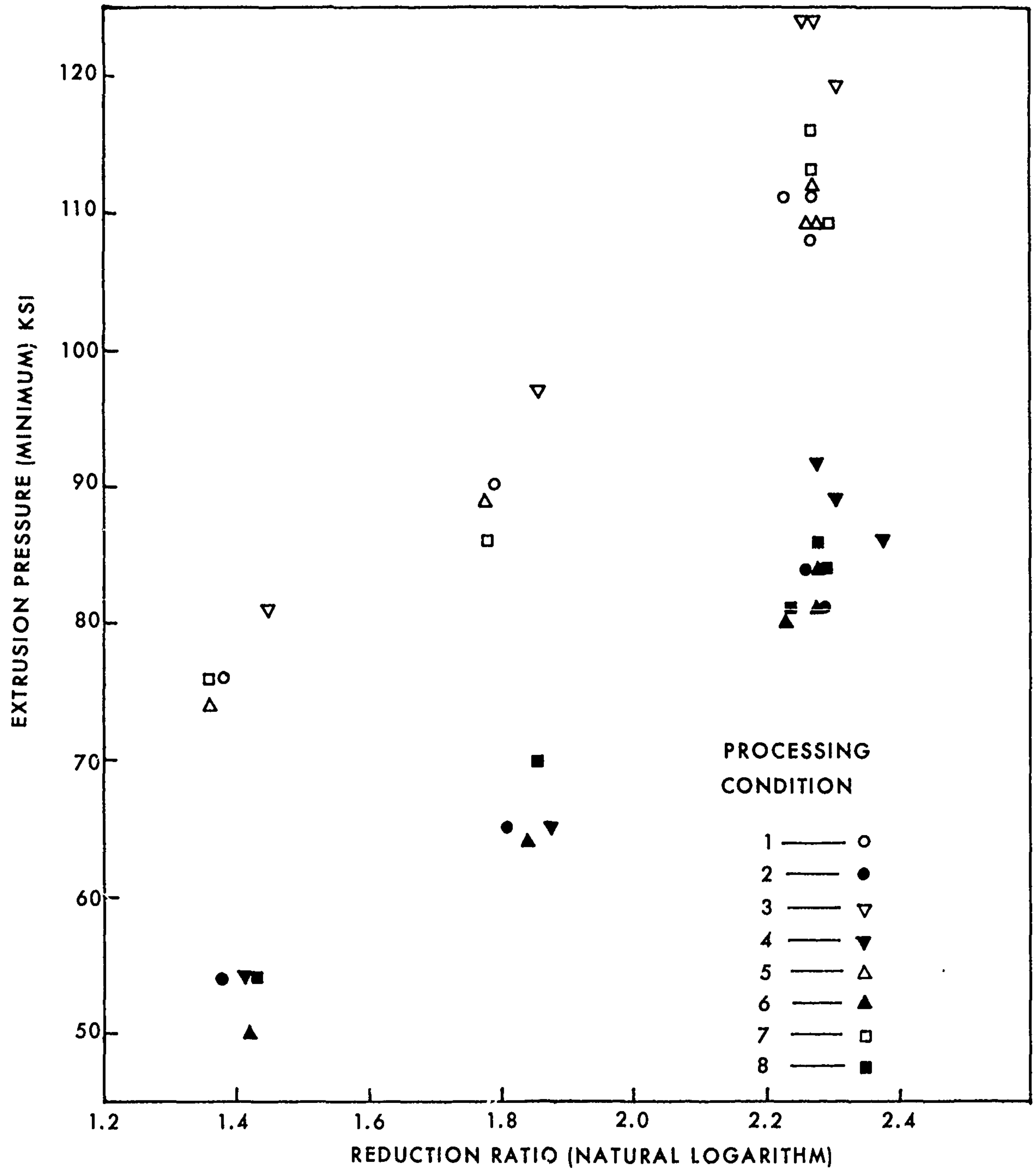


Figure 4. Extrusion Pressures Versus Reduction Ratio for Bar Stock (IM) and Powder Metal (PM) Beta III Titanium Alloy at 760°C (1400°F) and 954°C (1750°F).

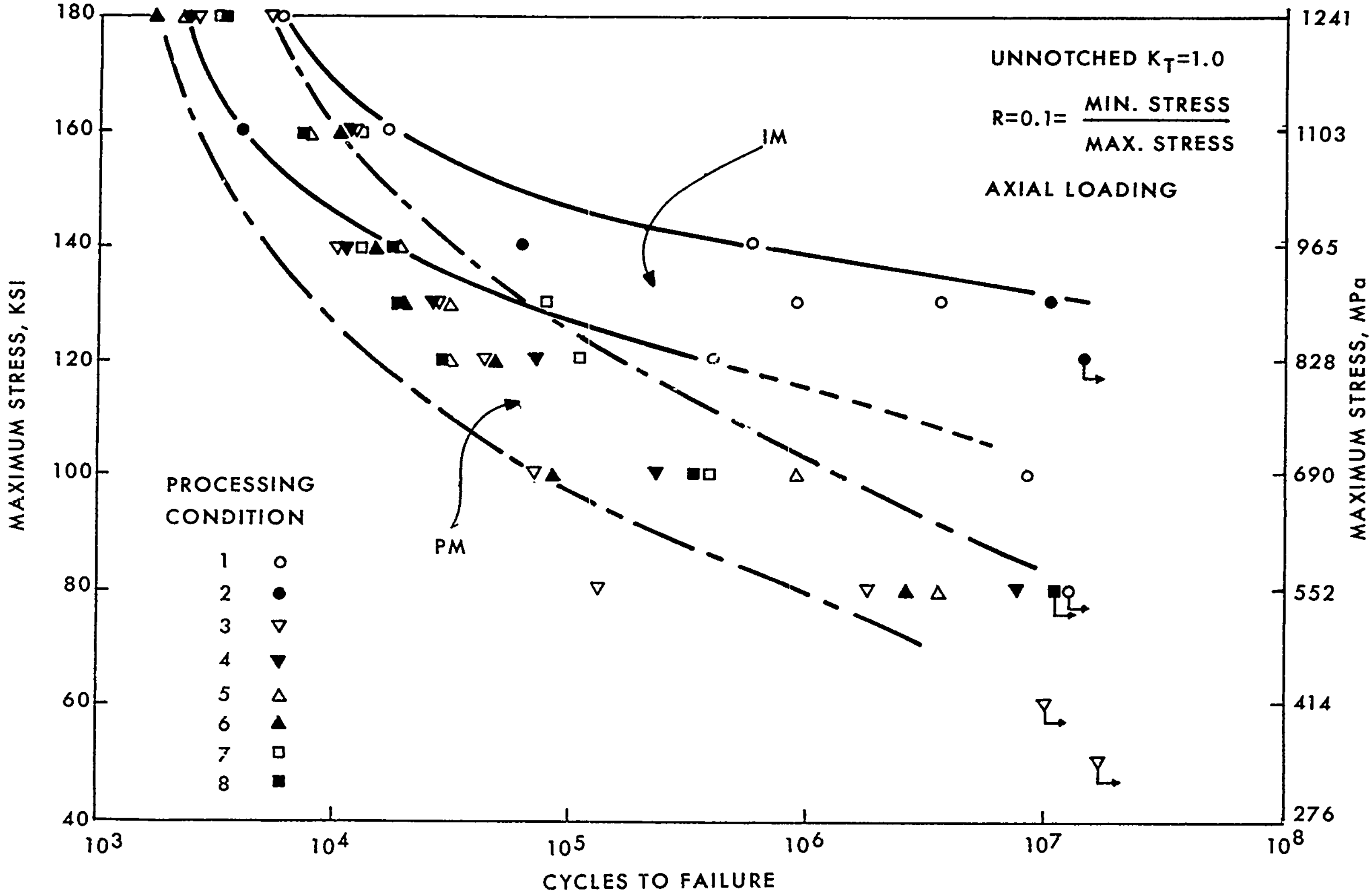


Figure 5. Room Temperature Fatigue Curves for Smooth Specimens Obtained from 760°C and 954°C Extrusions and in the STA Condition for both Powder and Wrought Product.

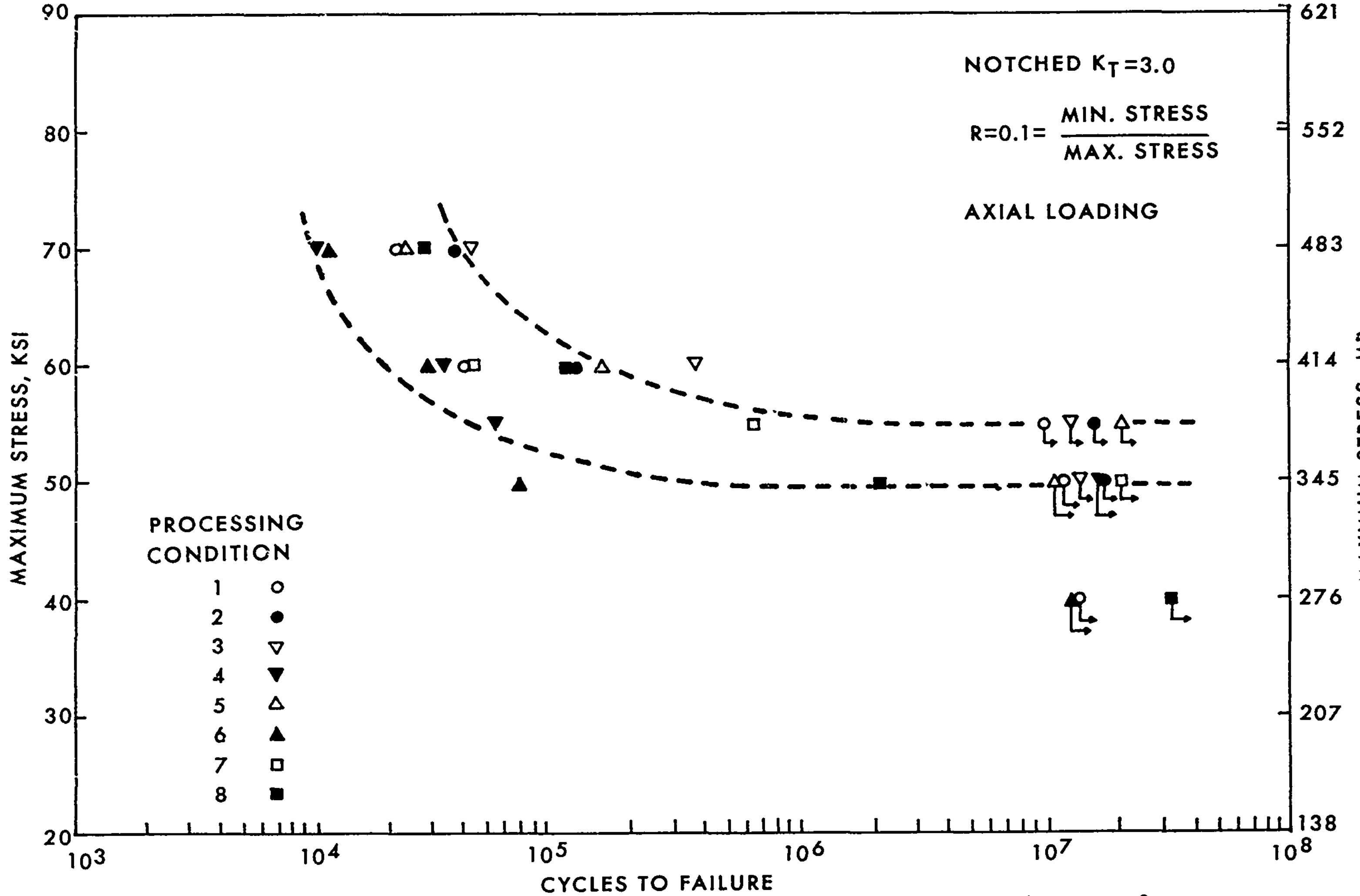


Figure 6. Room Temperature Fatigue Cruves for Notched Specimens Obtained from 760°C and 954°C Extrusions and in STA Condition for both Fowder and Wrought Product.

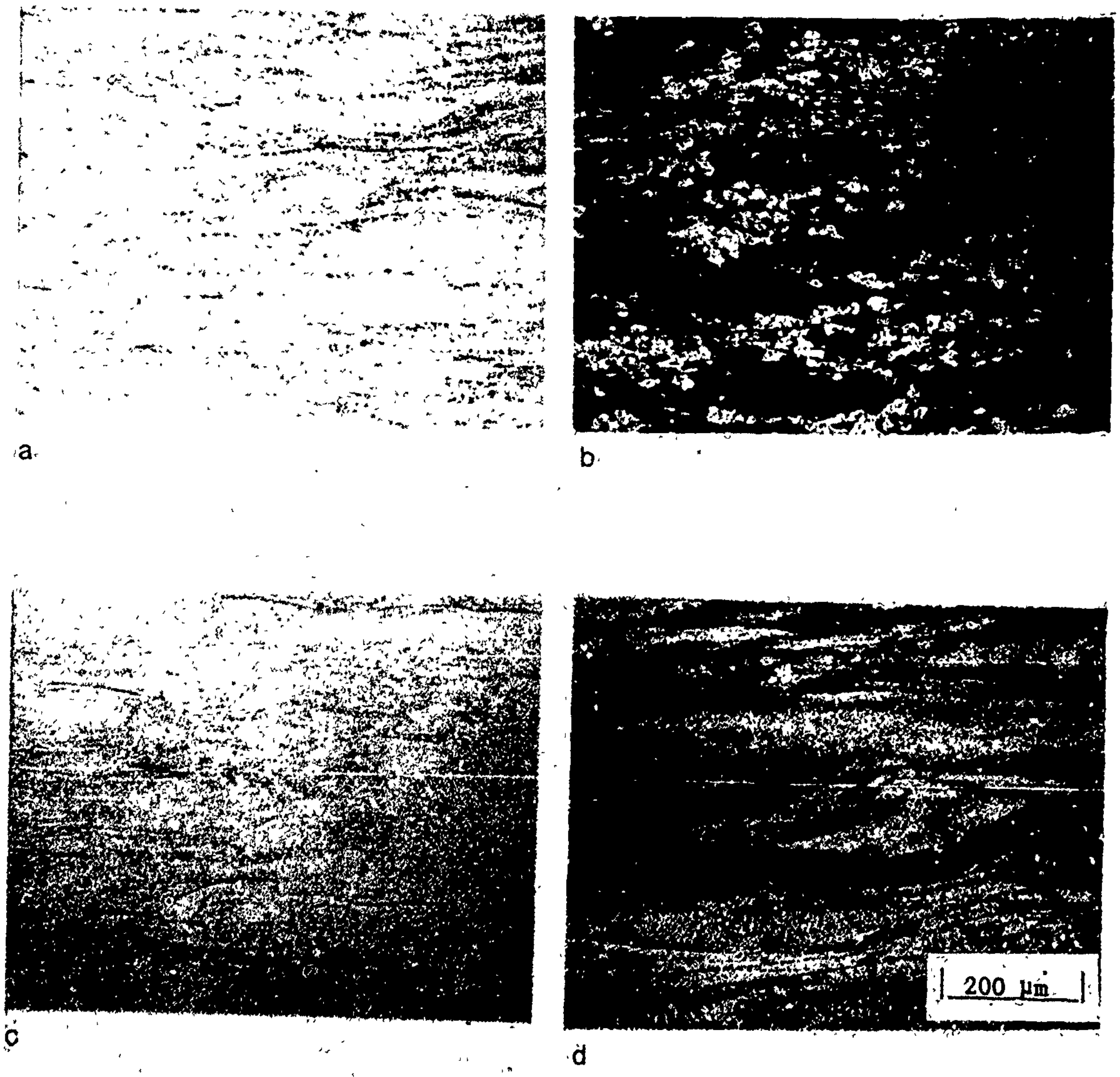


Figure 7. Micrographs of 4:1 Extrusions of Beta III in As-Extruded Condition. (A) Processing Condition 1, (B) Processing Condition 3, (C) Processing Condition 5 and (D) Processing Condition 7.

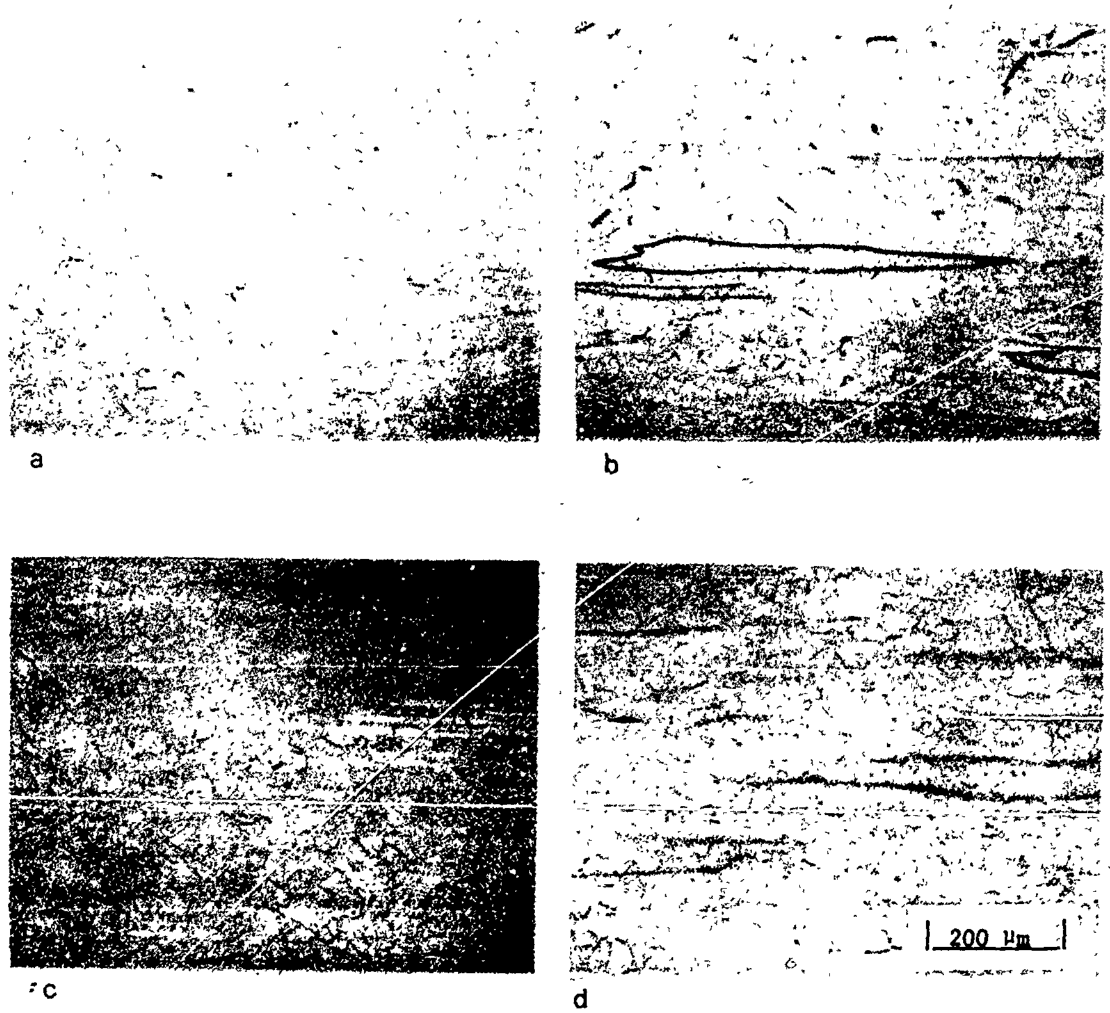


Figure 8. Micrographs of 4:1 Extrusions of Beta III in As-Extruded Condition. (A) Processing Condition 2, (B) Processing Condition 4, (C) Processing Condition 6 and (D) Processing Condition 8.

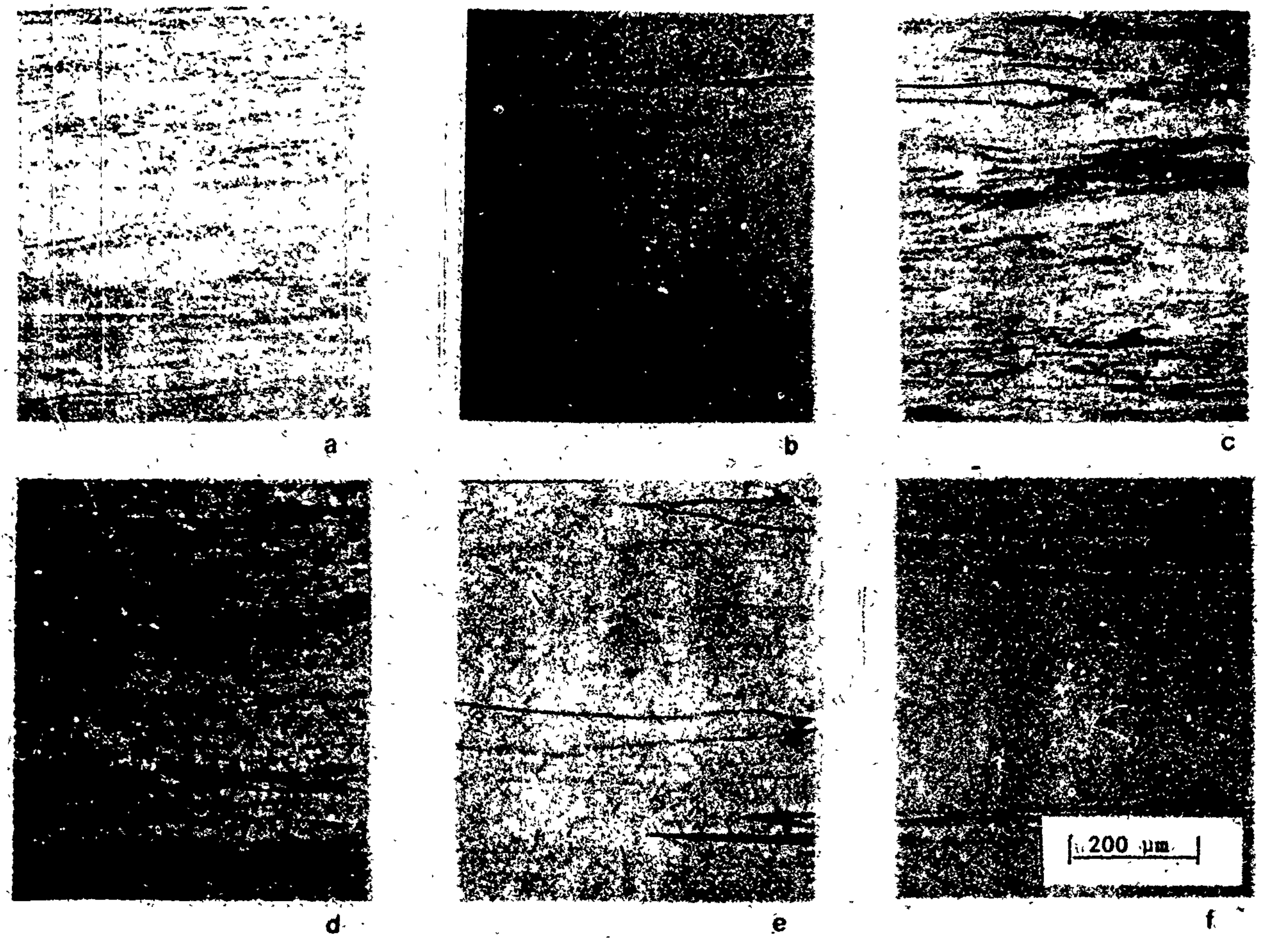


Figure 9. Microstructures of Longitudinal Sections of 10:1 Beta III Extrusions in the As-Extruded Condition. (A) Processing Condition 1, (B) Processing Condition 3, (C) Processing Condition 5, (D) Processing Condition 2, (E) Processing Condition 4 and (F) Processing Condition 6.

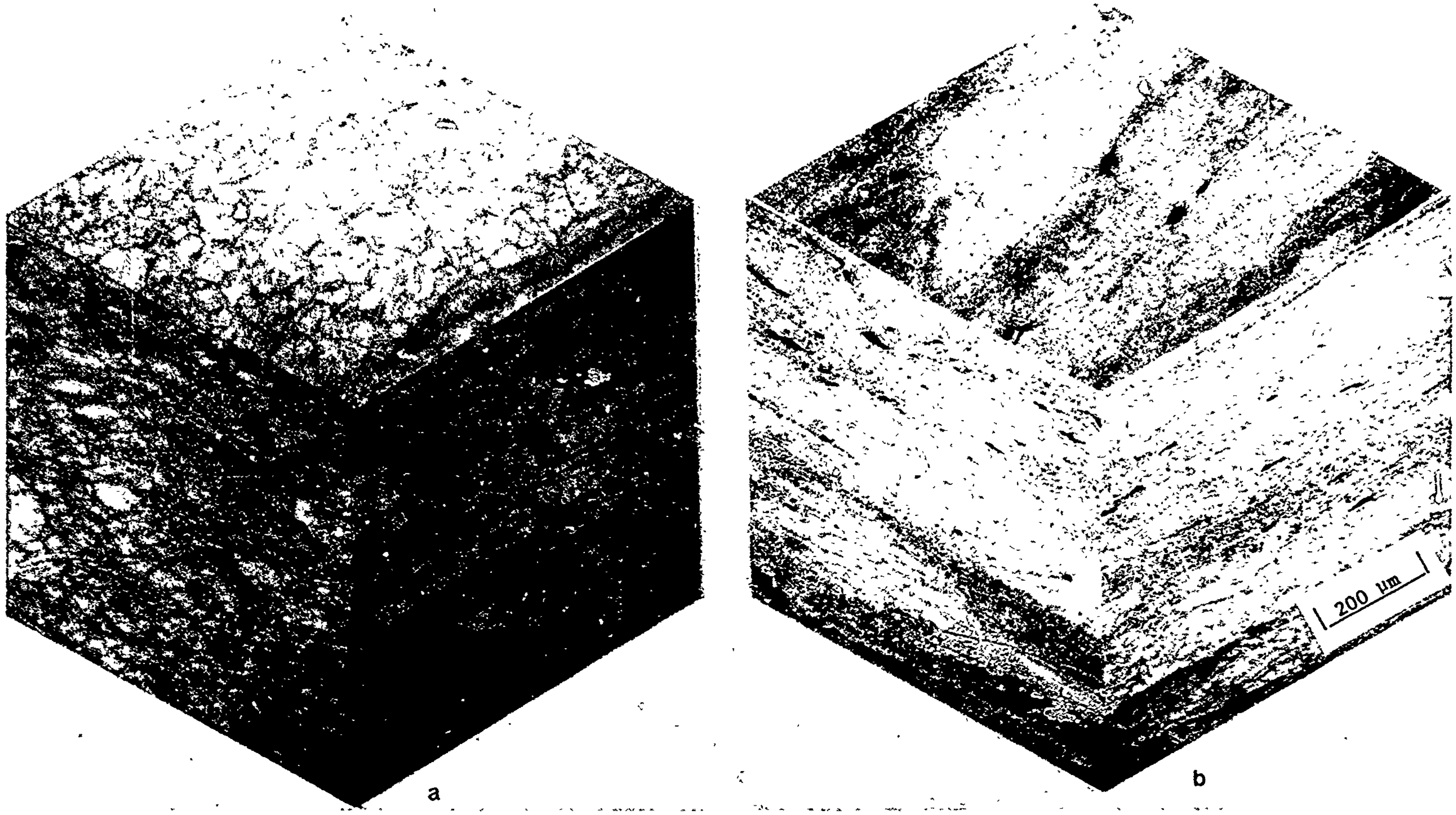


Figure 10. Micrographs of Beta III Forgings in STA Condition. (A) Processing Condition 3, (B) Processing Condition 7.

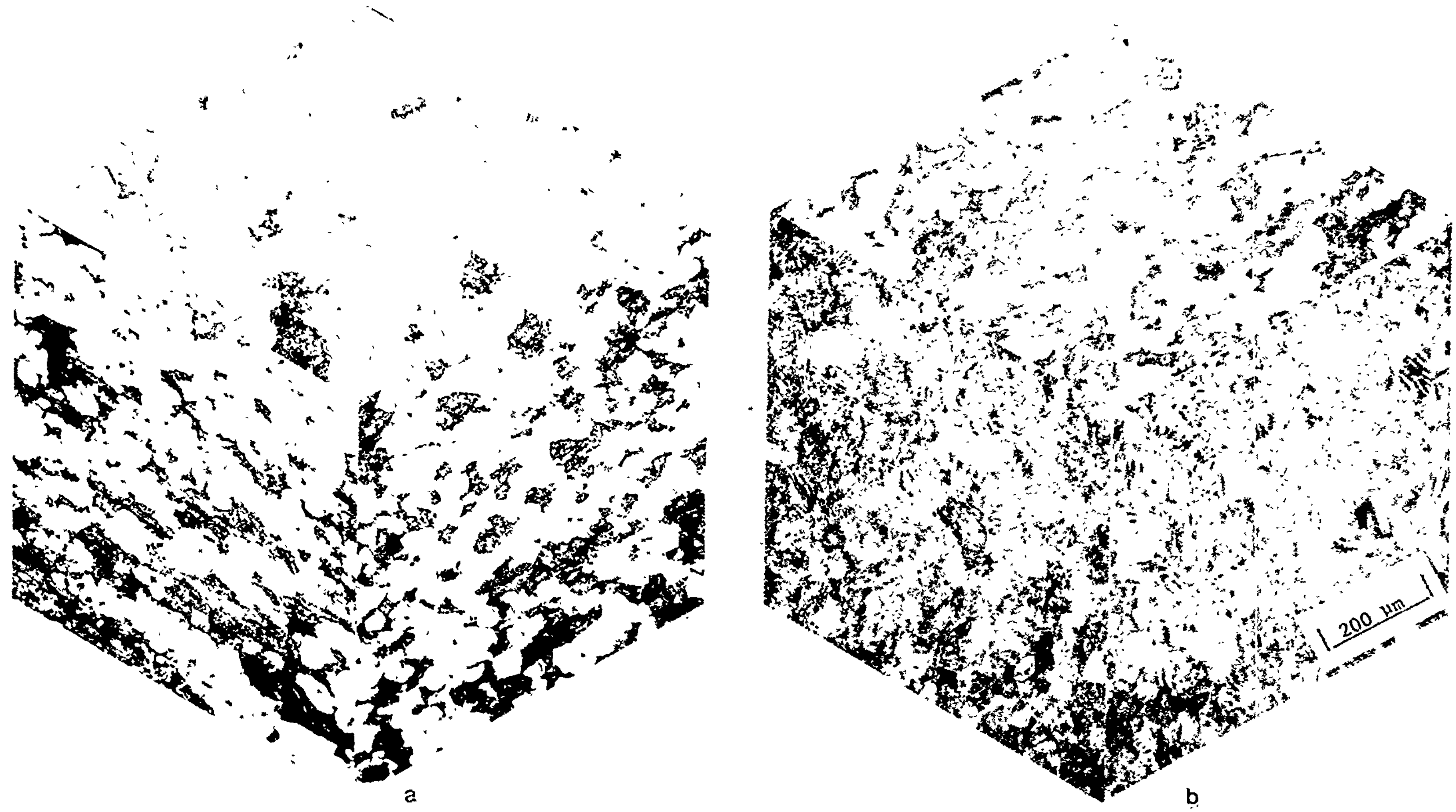


Figure 11. Micrographs of Beta III Forgings in Processing Condition 1. (A) STA Condition, (B) STA+OA Condition.

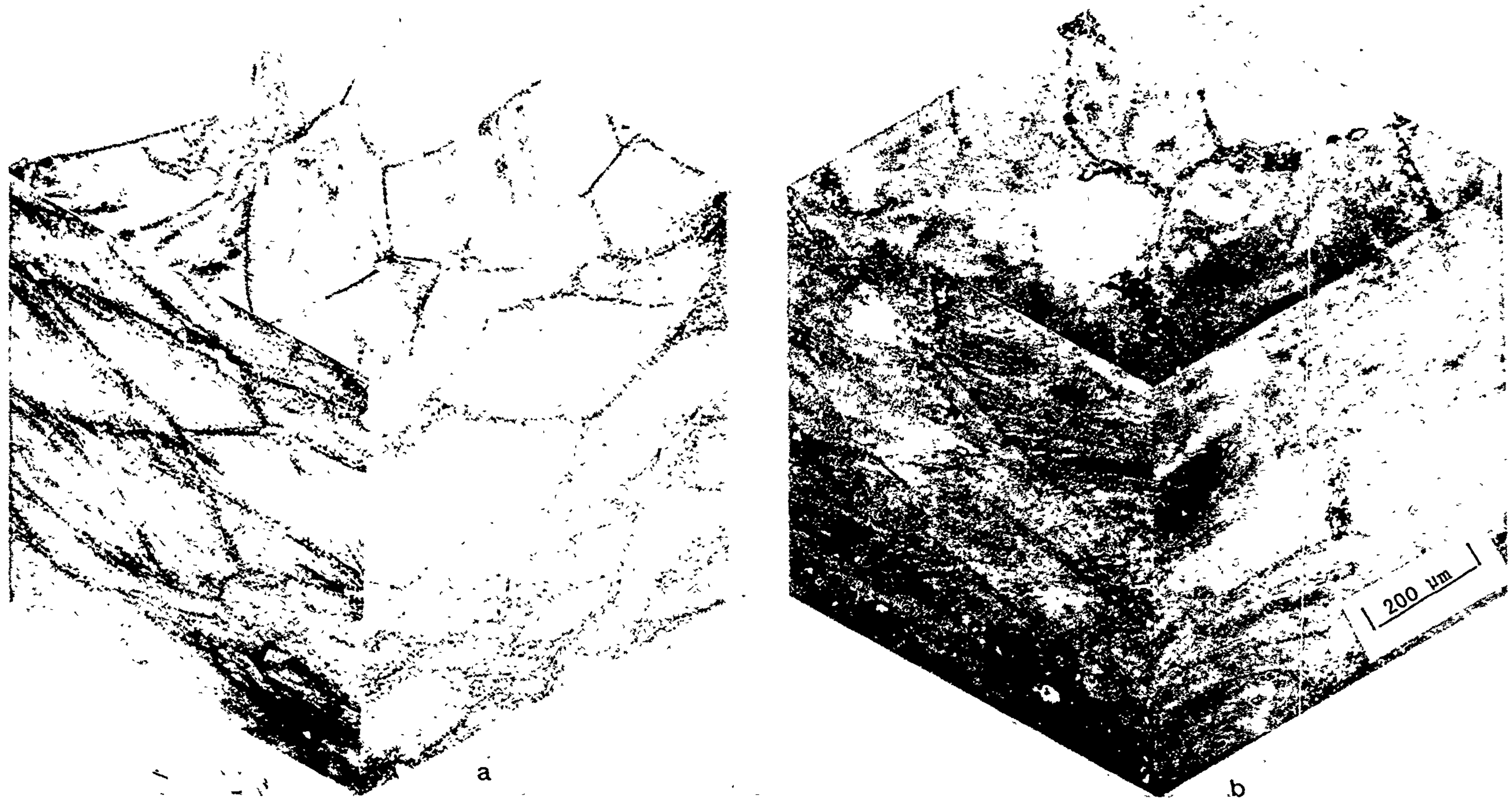


Figure 12. Micrographs of Beta III Forgings for Processing Condition 2. (A) STA Condition, (B) STA+OA Condition.

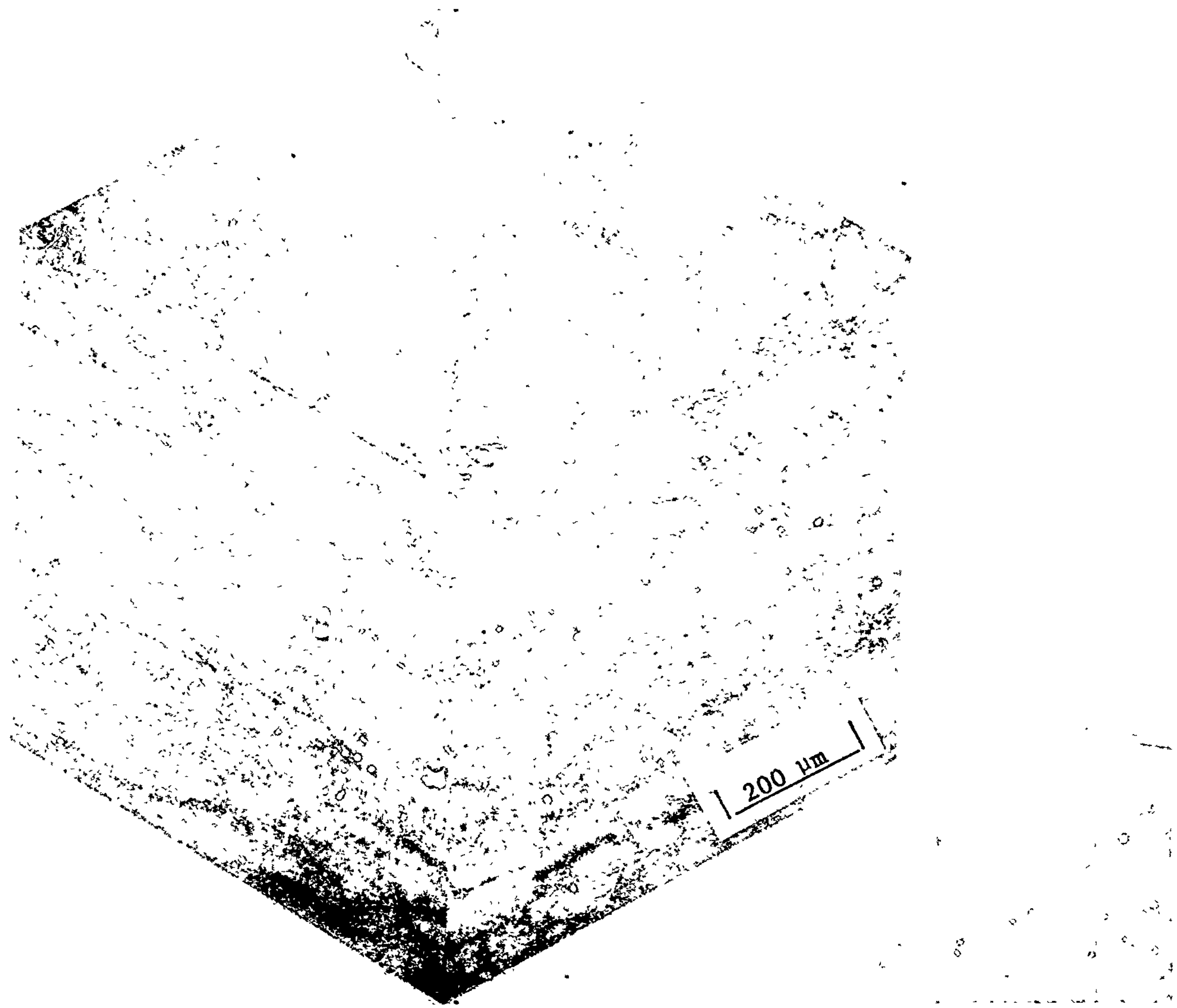


Figure 13. Micrograph of Beta III Forgings for Processing Condition 4 After STA Heat Treatment.

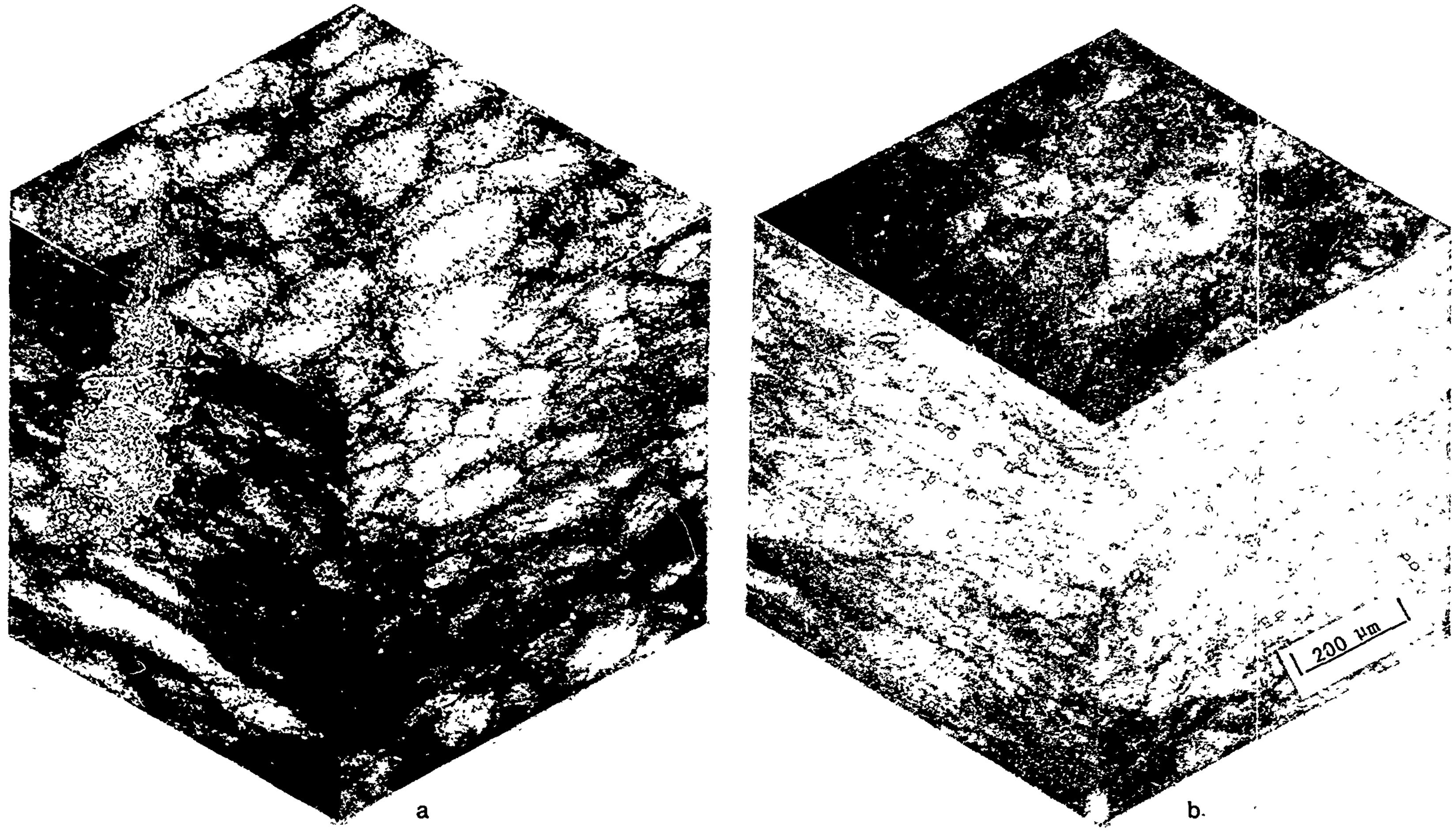


Figure 14. Micrographs of Beta III Forgings for Processing Condition 6. (A) STA Condition, (B) STA+OA Condition.

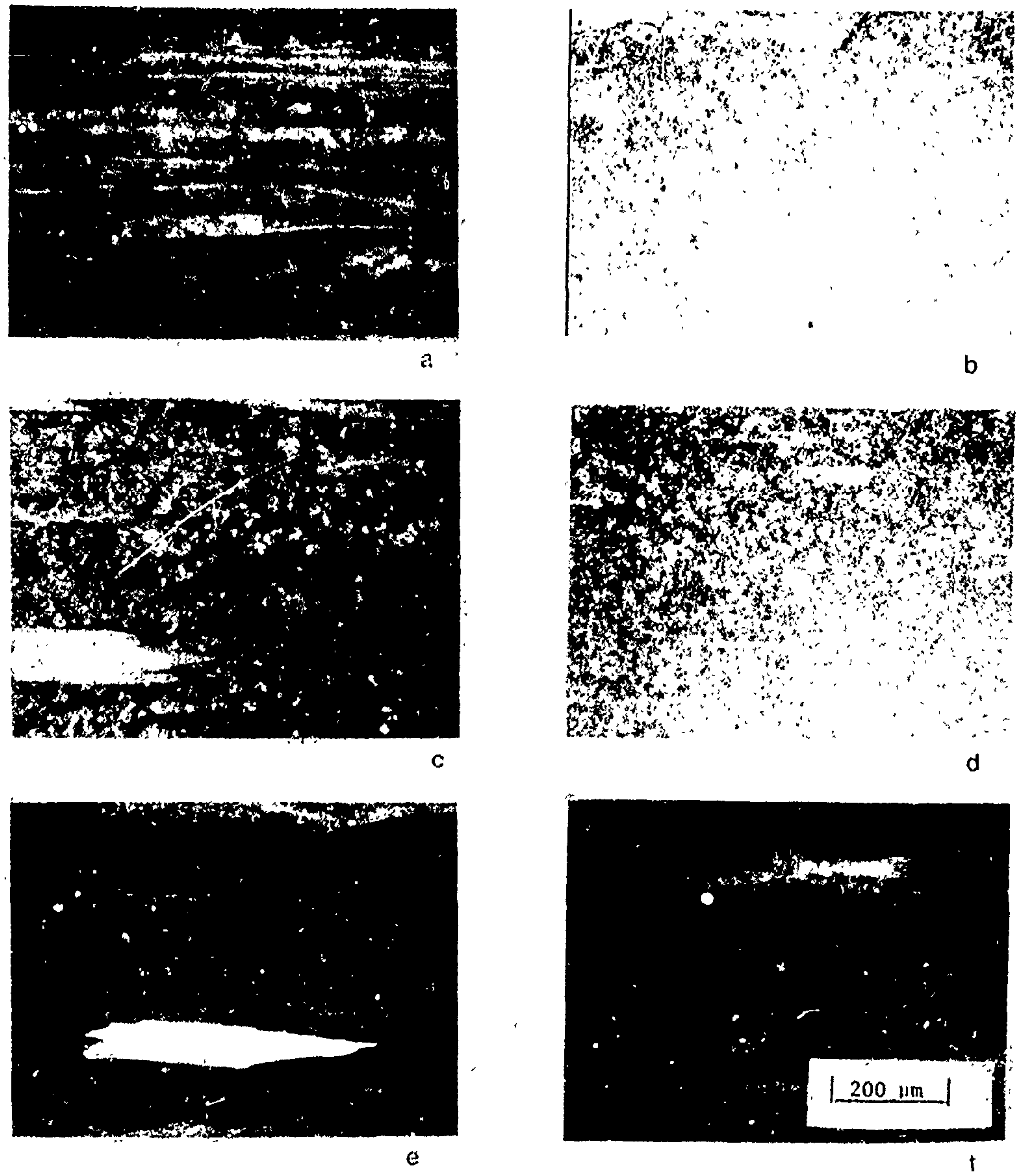


Figure 15. Micrographs of Longitudinal Sections of 10:1 Beta III Extrusions After Heat Treatment. (A) Processing Condition 1 and STA, (B) Processing Condition 1 and STA+OA, (C) Processing Condition 3 and STA, (D) Processing Condition 3 and STA+OA, (E) Processing Condition 5 and STA, (F) Processing Condition 7 and STA.

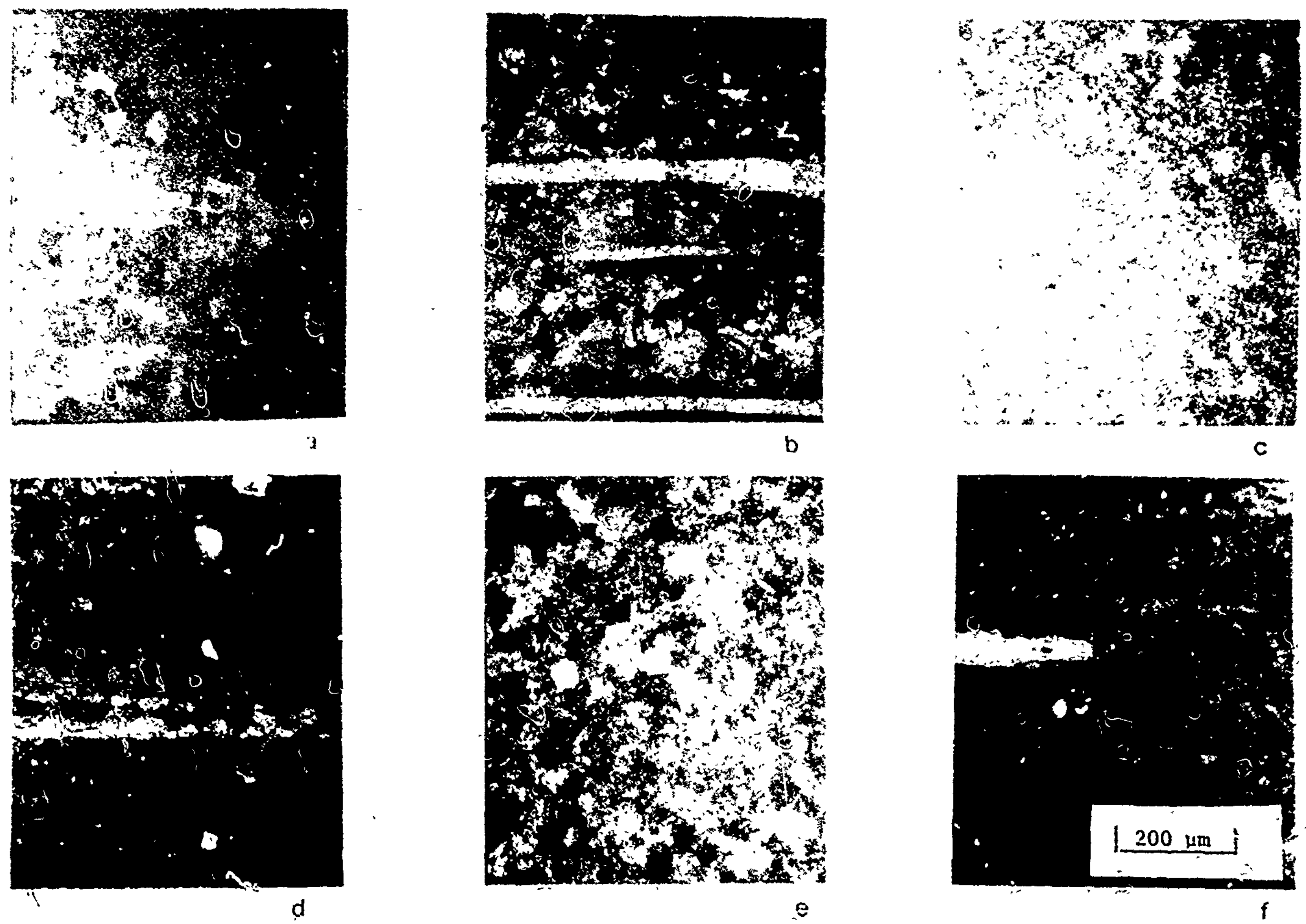


Figure 16. Micrographs of Longitudinal Section of 10:1 Beta III Extrusions After Heat Treatment. (A) Processing Condition 2 and STA, (B) Processing Condition 4 and STA (C) Processing Condition 4 and STA+OA, (D) Processing Condition 6 and STA, (E) Processing Condition 6 and STA+OA, (F) Processing Condition 8 and STA.

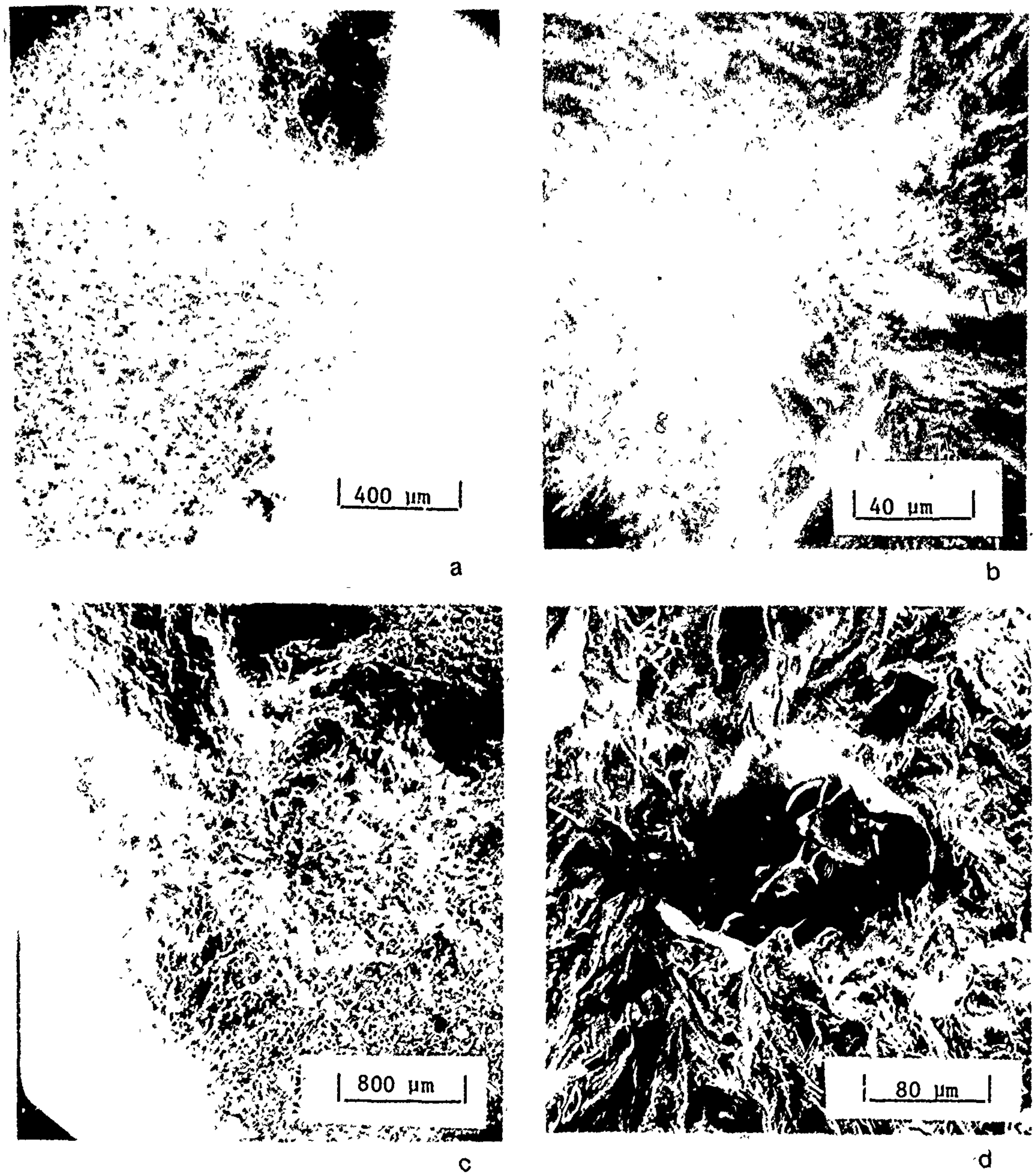


Figure 17. SEM of Fractured Surfaces of Beta III Smooth Fatigue Specimens in STA Condition. (A) and (B) Processing Condition 1 and 130 KSI, (C) and (D) Processing Condition 3 and 130 KSI.

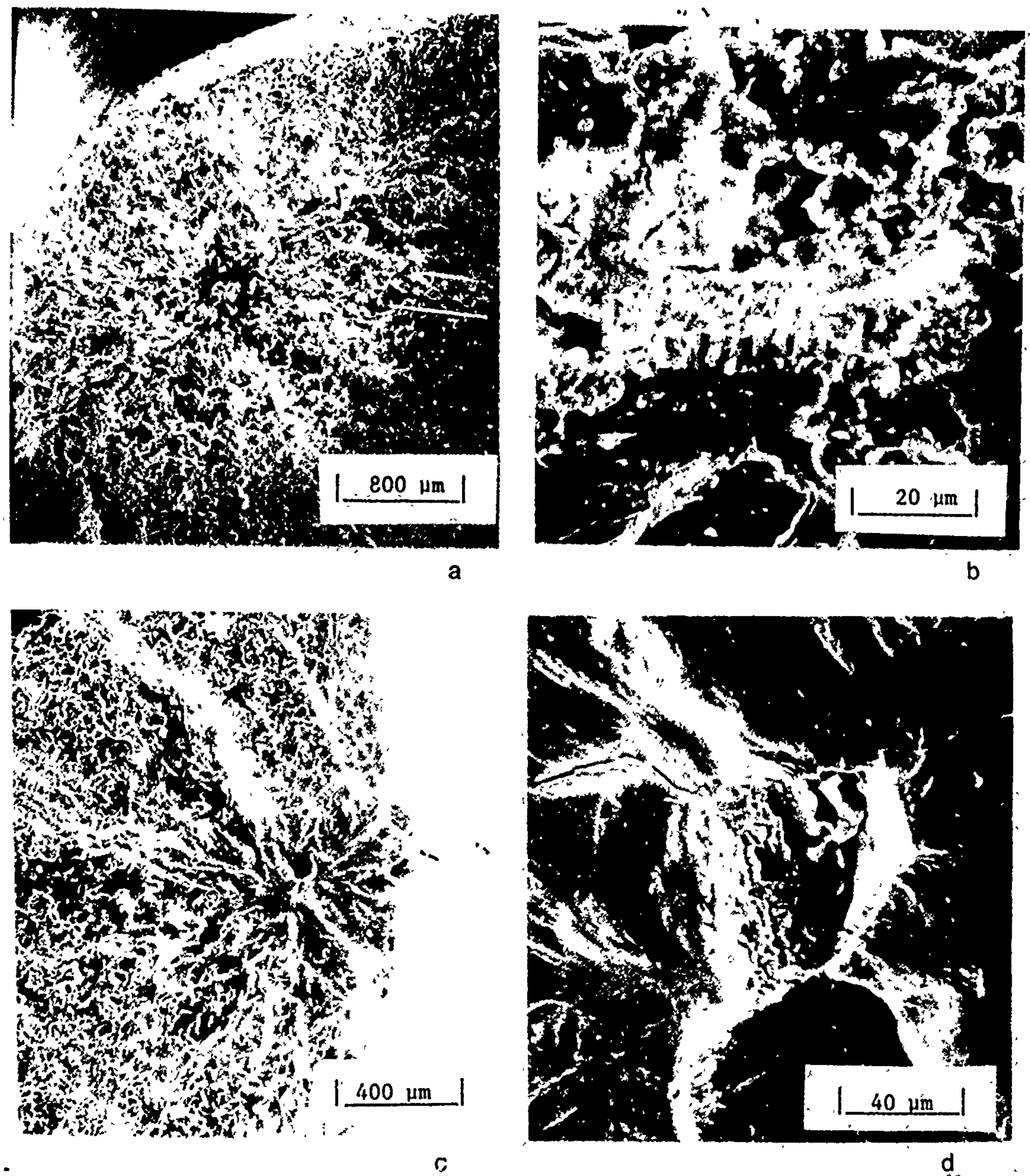


Figure 18. SEM of Fractured Surface of Beta III Smooth Fatigue Specimens in STA Condition. (A) and (B) Processing Condition 4 and 100 KSI, (C) and (D) Processing Condition 6 and 130 KSI.

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